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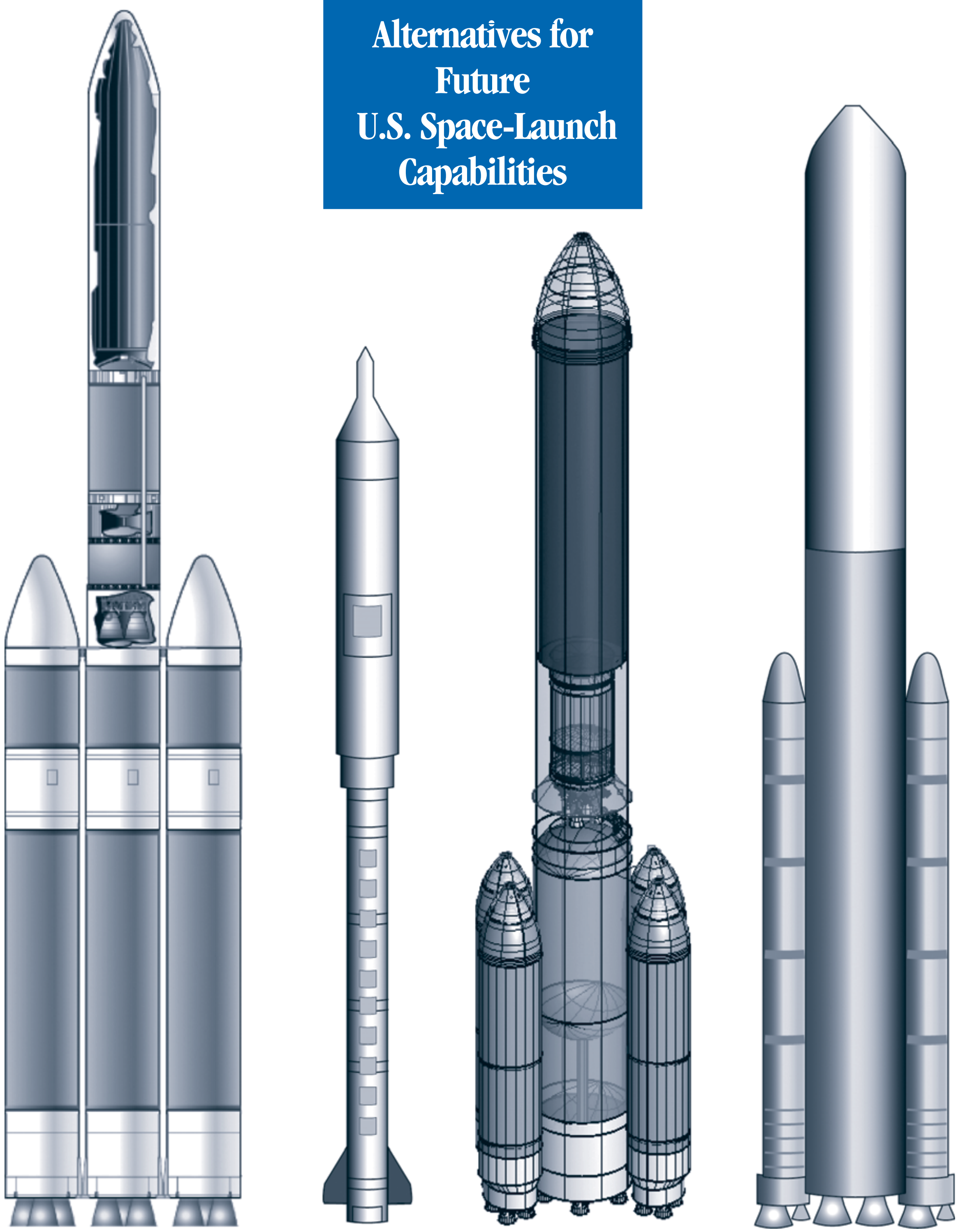
CONGRESSIONAL BUDGET OFFICE

A CBO STUDY

OCTOBER 2006

Alternatives for Future U.S. Space-Launch Capabilities



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October 2006

The Congress of the United States ■ Congressional Budget Office

Note

Unless otherwise indicated, all years referred to in this study are federal fiscal years, and all dollar amounts are expressed in 2006 dollars of budget authority.

Preface

Currently available launch vehicles have the capacity to lift payloads into low earth orbit that weigh up to about 25 metric tons, which is the requirement for almost all of the commercial and governmental payloads expected to be launched into orbit over the next 10 to 15 years. However, the launch vehicles needed to support the return of humans to the moon, which has been called for under the Bush Administration's Vision for Space Exploration, may be required to lift payloads into orbit that weigh in excess of 100 metric tons and, as a result, may constitute a unique demand for launch services.

What alternatives might be pursued to develop and procure the type of launch vehicles necessary for conducting manned lunar missions, and how much would those alternatives cost? This Congressional Budget Office (CBO) study—prepared at the request of the Ranking Member of the House Budget Committee—examines those questions. The analysis presents six alternative programs for developing launchers and estimates their costs under the assumption that manned lunar missions will commence in either 2018 or 2020. In keeping with CBO's mandate to provide impartial analysis, the study makes no recommendations.

Paul B. Rehmus wrote the study under the supervision of J. Michael Gilmore. Raymond Hall prepared the cost estimates for the alternative launch vehicle programs considered in the study. Robert Dennis, Douglas Hamilton, David Moore, and Thomas Woodward of CBO provided comments on an earlier draft, as did representatives from several U.S. aerospace companies and the National Aeronautics and Space Administration. Marshall Kaplan of the Institute for Defense Analyses reviewed the study and provided insights. (The assistance of external reviewers implies no responsibility for the final product, which rests solely with CBO.)

Loretta Lettner edited the study, and Christine Bogusz and Kate Kelly proofread it. Cynthia Cleveland and Allan Keaton formatted the tables, Maureen Costantino designed the cover, and Christian Howlett prepared the study for publication. Lenny Skutnik printed the initial copies, and Simone Thomas prepared the electronic version for CBO's Web site (www.cbo.gov).

Donald B. Marron

Donald B. Marron
Acting Director

October 2006

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Introduction and Summary

A Presidential directive issued on January 14, 2004—called the new Vision for Space Exploration (VSE)—set out goals for future exploration of the solar system using manned spacecraft. Those goals included returning to the moon no later than 2020. Although sufficient capabilities exist to meet the projected needs of both the U.S. commercial sector and the government for launching unmanned payloads into space through 2020, that is not the case for manned space flight. The proposed return to the moon called for under the VSE and now planned by the National Aeronautics and Space Administration (NASA) could require the development of the capacity to launch payloads weighing more than 100 metric tons (mt).[1] No launch vehicles currently exist that can handle payloads weighing more than about 25 mt. Thus, NASA's plans for manned space flight beyond low earth orbit (LEO) could require a significant increase in launch capability.[2] How that capability could be provided and at what cost are the focal points of this study.

In considering manned lunar missions, the Congressional Budget Office (CBO) explored alternatives that would use existing launch vehicles; those that would require minor modifications to the designs of existing launchers (termed "close derivatives"); as well as those that would call for major modifications to existing vehicle designs to develop essentially new and much more capable launchers.[3] All of the alternatives would require multiple launches to assemble in LEO the fuel and hardware needed to fly to the moon. Under the alternatives, CBO estimates, the costs to develop and procure launch vehicles that could support a manned lunar mission in 2018 (under a more ambitious schedule) would range from $26 billion to $38 billion. NASA's projection of funding is $30 billion. The use of less capable existing or close-derivative launchers could be less costly but would require up to eight launches to assemble a single lunar mission. Using the new and more capable launchers considered by CBO would be more costly but could reduce to two the number of launches needed per lunar mission. The greater the number of launches needed to assemble a mission, the greater the complexity of the mission—including both the need to perform on-orbit assembly of the mission's components and the risk that at least one launch would fail, putting the success of the mission at risk. Thus, there is a trade-off between the overall costs of launch vehicles and the risk of mission failure.

Current Launch Capabilities and Projected Worldwide Demand

Excluding manned flight beyond LEO, U.S. needs for launch vehicles involve putting into orbit payloads (both commercial and governmental in origin) that weigh less than 25 metric tons, with the majority weighing less than 12 mt. Typical payloads consist of satellites (usually designed to track weather, facilitate communications, aid scientific research, or conduct surveillance) or mission

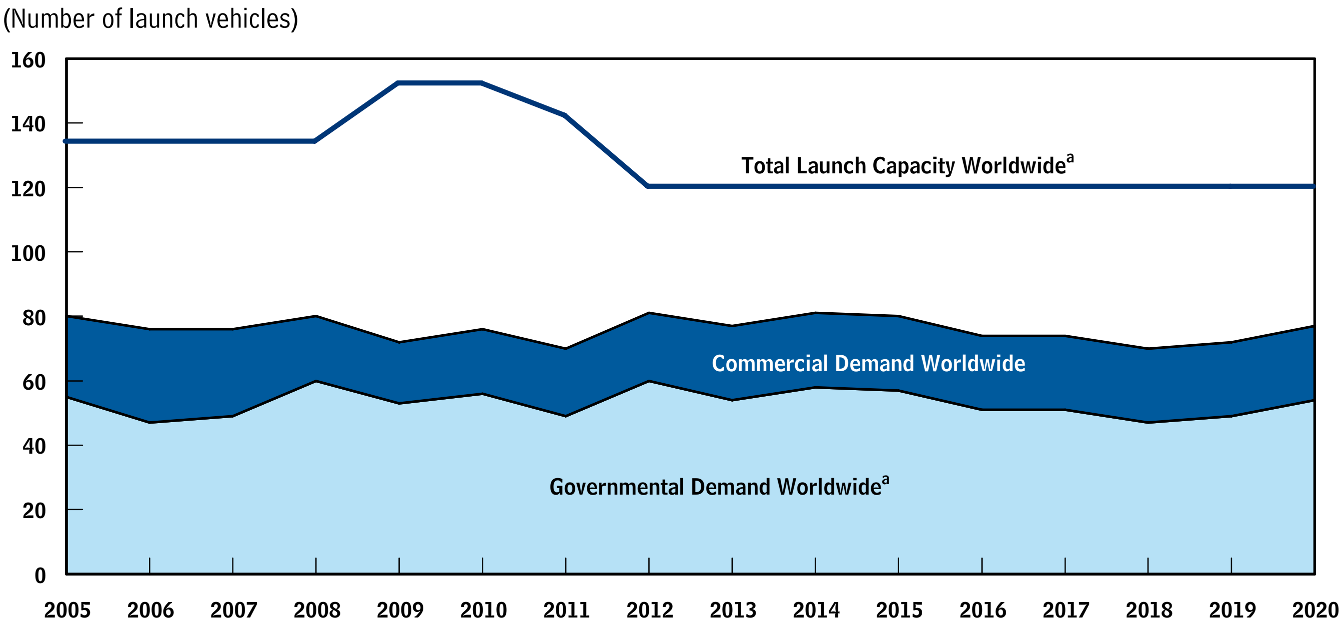
1. A metric ton is 1,000 kilograms, or about 1.1 short tons; a short ton is 2,000 pounds.

2. Low earth orbit is defined as one of a group of circular orbits that lies between the appreciable atmosphere (which is about 120 nautical miles, or nm, high) and the Van Allen radiation belt (which is about 1,000 nm high) and has an inclination to the equator of less than 60 degrees. A variety of other orbit classes are recognized. Those with inclinations of greater than 60 degrees are referred to as polar orbits. Geosynchronous orbits (GSOs), which are also known as geostationary orbits, are about 22,000 nm high and allow satellites to remain over a single point above the Earth. Another class of orbits is the set of elliptical geosynchronous transfer orbits (GTOs) that are often used for transitions between LEOs and GSOs.

3. CBO characterizes as close derivatives those new launch vehicles that are substantially similar to existing systems. The essentially new and much more capable launchers are termed "super-heavy" launchers.

Summary Figure 1.

Worldwide Capacity and Demand for Launch Services



Source: Congressional Budget Office based on data provided by the Federal Aviation Administration and the Futron Corporation.

Note: Capacity is the number of launches that existing infrastructure and production facilities can support if fully manned and funded. Demand is either the number of launches required on historical launch manifests or current projections of future launch manifests. For a variety of reasons, therefore (because of delays in the availability of payloads, for instance), the number of actual launches usually ends up being less than the demand reflected on manifests.

a. Excludes the National Aeronautics and Space Administration's Vision for Space Exploration initiative.

support (such as consumables, parts, or manpower) for the International Space Station, or ISS. Current estimates from various sources of worldwide launch capacity for payloads weighing less than about 25 mt range from approximately 120 to 150 launches per year. According to projections obtained by CBO, worldwide demand for launching such payloads through 2020 ranges between 70 and 80 launches a year (see Summary Figure 1). Projected capacity is an estimate of the maximum number of launches that existing launch pads and launch vehicle manufacturing facilities can support if fully manned and funded. Projected demand includes all launches now expected worldwide for either commercial or governmental purposes. The projections obtained by CBO indicate that maximum worldwide launch capacity for payloads of less than 25 mt will exceed demand by about 50 percent to as much as 100 percent.

Launch Needs for Manned Lunar Missions

The flights to the moon conducted during the Apollo program (from 1966 to 1972) required the capacity to launch about 140 mt into LEO. That capability was provided by a single, expendable launch vehicle, the Saturn V. The details of the lunar missions being planned by NASA under the VSE could be more ambitious than those conducted under the Apollo program. (One motivation for resuming lunar missions is to help enable eventual manned space flight beyond the moon—including to Mars.) NASA also plans to use the spacecraft that would be used to fly to and return from the moon—the crew exploration vehicle, or CEV—to service the ISS after the retirement of the space shuttle in 2010. NASA has estimated that the net effect of those changes relative to Saturn/Apollo might increase the weight of a manned lunar mission by about 10 percent.

The alternatives considered by CBO for returning humans to the moon fall into two categories: those that would use existing heavy launchers and those that would require developing new launch systems. The new launch systems considered by CBO include close derivatives of existing systems—launchers that could lift somewhat heavier payloads than current systems—as well as new, larger launchers, referred to as super heavies, that could lift payloads weighing 100 mt or more. Generally, the alternatives considered by CBO have also been considered by NASA or its contractors, including Boeing, Lockheed Martin, and ATK Thiokol, as NASA continues to develop its plans for returning humans to the moon.

Existing Heavy-Lift Launch Vehicles

The existing U.S. heavy-lift launch systems considered by CBO include NASA's space shuttle, Boeing's Delta IV Heavy (D4H) variant of the U.S. Air Force's set of evolved expendable launch vehicles (EELVs), and the most capable variant of Lockheed Martin's Atlas V Medium (A5M) EELV.[4] The Delta IV Heavy has a lift capacity of 25 mt, the most capable variant of the Atlas V Medium has a lift capacity of 20.5 mt, and the space shuttle can lift a payload weighing 18 mt.[5] Therefore, using existing U.S. heavy-lift launch systems would require six to eight launches to propel into LEO all of the mass necessary to execute a manned lunar mission.

Although in the Apollo program the payload for lunar exploration was lifted into LEO with one launch, NASA considered options for the VSE program that require multiple launches. The use of multiple launches has wide-ranging implications for both safety and cost savings. In particular, such a strategy could theoretically permit the use of existing launchers rather than require the development of a new launch vehicle with lift capability exceeding 100 mt. (That would translate into less capable but individually cheaper launch vehicles.) Using multiple launches would also mean, again theoretically, that a single launch failure would not cause the failure of an entire mission. Further, multiple launches could permit the crew to be lifted on a launcher designed to be highly reliable, while less reliable launchers were used to lift the other, heavier elements of the payload, or cargo.

There are, however, potential drawbacks associated with using multiple launches. Multiple launches could require time to execute (perhaps several months), during which subcomponents of the full payload, some likely containing cryogenic fuels, must remain in LEO. Notwithstanding improved techniques for insulating cryogenic fuels, on-orbit storage of such fuels for many months would be a challenge (because of leakage) and would require that fuel in excess of the amounts actually burned be lifted into LEO, thereby potentially increasing the total number of launches needed. The subcomponents would also have to be assembled into a complete spacecraft in orbit, potentially requiring the development of a capability for reliable and fully automated rendezvous, docking, and on-orbit assembly that the United States has never attempted.

Relying on multiple launches could also complicate mission planning because the more launches that needed to be executed to complete a mission, the less the probability that all of those launches would succeed. A launch failure or failure of an on-orbit rendezvous and docking would render a payload subcomponent unusable, and which subcomponent might fail could not be predicted a priori. Thus, a complete set of additional payload subcomponents might be needed to ensure completion of a successful mission.

New Launch Vehicles: Close Derivatives of Existing Systems

Although representative close derivatives selected by CBO have the capability to lift payloads two to four times heavier than existing launchers, that increase in payload weight would be achieved by making major modifications to just a few components of an existing launch system rather than major modifications to nearly all of its components. In this study, CBO analyzed the cost and performance of close-derivative launch vehicles

4. The evolved expendable launch vehicles are the Air Force's current fleet of launchers designed to take heavier payloads (weighing between 5 mt and 25 mt) into orbit.

5. The weight that a launch vehicle can lift into orbit varies depending on the orbit and launch location. The orbit referenced here is circular, 220 nautical miles high, and inclined 28.6 degrees to the equator with launch from the Kennedy Space Center. For this particular orbit, the shuttle's performance is taken from S.J. Isakowitz and others, *International Reference Guide to Space Launch Systems*, 4th ed. (Reston, Va.: American Institute of Aeronautics and Astronautics, 2004), p. 434.

that could be used to execute a manned lunar mission similar to those considered by NASA and members of the U.S. space-launch industry. The close derivatives considered by CBO included modified versions of the space shuttle and its components, as well as modified versions of both the Atlas and Delta versions of the EELV. In all cases, the launch vehicles used to lift a spacecraft and its crew into LEO, called crew carriers, are distinct from cargo carriers, which are used to lift the remaining payload.

The specific close-derivative launch vehicles considered by CBO include the following:

- **The Five-Segment "Stick" (crew carrier/lift capacity, 26 mt).** This launch vehicle's antecedent is based on the four-segment solid rocket booster (SRB), a pair of which now help lift the shuttle into orbit. (The main propulsion system for the shuttle is composed of three "sticks," two four-segment SRBs attached to the central external tank, or ET—the third stick.) The SRBs are composed of individual cylindrical sections, each of which contains a casting of solid fuel. The single five-segment stick considered here would consist of five such sections, which constitute the first stage of the rocket, as well as a new second stage (with an independent liquid-fuel propulsion system) mounted on top of the SRB. That additional stage is needed to provide the capability to lift 26 mt into LEO.

- **The Side-Mount (cargo carrier/lift capacity, 77 mt).** Also conceptually similar to the space shuttle, the Side-Mount would use the space shuttle propulsion system with a cargo canister replacing the airplane-like orbiter. The payload that the side-mount could lift into LEO would be about 77 mt.

- **The Delta IV Heavy with Modifications, or D4H with Mods (crew carrier/lift capacity, 21 mt).** Based on the existing Delta IV Heavy developed by Boeing, the D4H with mods would be able to lift about 21 mt into LEO.

- **The Delta IV Medium Plus, or D4M+ (crew carrier/lift capacity, 18 mt).** Relative to the single-stick Delta IV Medium (D4M) EELV, from which it is derived, the D4M+ would have an expanded first-stage central core with additional engines and an expanded second stage. Those modifications would enable the D4M+ to lift about 18 mt into LEO.

- **The Delta IV Heavy Plus, or D4H+ (cargo carrier/lift capacity, 40 mt).** The three-stick D4H is built using three of the first-stage central cores used for the D4M. Similarly, the D4H+ would use three of the central cores of the D4M+, enabling it to lift about 40 mt of cargo into LEO.

- **The Atlas V Medium Plus, or A5M+ (crew carrier/lift capacity, 24 mt).** This single-stick vehicle is based on the Atlas V Medium (A5M) EELV, developed by Lockheed Martin. Relative to the existing A5M launcher, the A5M+ would have a larger first-stage central core and an upgraded second stage providing the capability to lift about 24 mt into LEO.

- **The Atlas V Heavy Plus, or A5H+ (cargo carrier/lift capacity, 74 mt).** This Atlas-derived cargo carrier would be based on the A5M+ crew carrier. The first stage of the A5M+ would serve as the basis for this three-stick vehicle. Relative to the A5M+, the A5H+ would also feature additional engines in its second stage. It would have the capability to lift about 74 mt into LEO.

New Launch Vehicles: Super Heavies

The super-heavy launch vehicles considered by CBO could lift payloads of 100 metric tons or more into low earth orbit. In general, those prospective launchers would require significant and relatively expensive upgrades to many—if not all—of the major systems that compose existing launchers. CBO considered super-heavy launch vehicles that would use components of the space shuttle, as well as launchers that would represent new and much more capable designs incorporating selected components—primarily engines—used on the current EELVs.

The specific super-heavy launchers considered by CBO include the following:

- **The Top-Mounted, Shuttle-Derived Super Heavy (cargo carrier/lift capacity, 125 mt).** In the January 2006 release of the President's 2007 budget, this cargo launch vehicle was identified as NASA's recommended solution for supporting manned lunar missions.[6] Because many of its major components would be drawn from the space shuttle, CBO refers to the vehicle as the shuttle-derived super heavy. It would be

6. See Office of Management and Budget, *Budget of the United States Government, Fiscal Year 2007* (January 2006).

about the size of the Saturn V rocket used for the Apollo flights to the moon, and its payload to LEO would be about 125 mt. It would use two five-segment SRBs (as opposed to the shuttle's two four-segment SRBs). The five-segment SRBs would be mounted on the sides of an elongated version of the shuttle's existing external tank, which would be modified to house five expendable versions of the existing (reusable) space shuttle main engines (SSMEs).[7] A large cargo canister, or "shroud," would be mounted on top of the tank-SRB assembly.

- **The Longfellow (cargo carrier/lift capacity, 108 mt).** This launch vehicle—proposed by an industry consortium that includes Boeing, Lockheed Martin, and ATK Thiokol—would resemble the shuttle-derived super heavy, but several aspects of its design would be different. In particular, it would use less expensive engines in its first stage and would be taller to accommodate a second stage. The Longfellow would be able to lift about 108 mt into LEO.

- **The Delta Super Heavy (cargo carrier/lift capacity, 146 mt).** The closest antecedent of this vehicle—proposed by Boeing—is the D4H. This launcher, however, would incorporate many changes relative to either the existing D4H or the prospective D4H+. Those changes include the use of three expanded first-stage cores 8 meters in diameter. The largest of the super heavies considered by CBO, this launcher would be capable of lifting the largest payload into LEO—about 146 mt.

- **The Atlas Super Heavy (cargo carrier/lift capacity, 135 mt).** The closest antecedent of this vehicle—proposed by Lockheed Martin—would be the Atlas V Heavy Plus. Relative to that prospective launcher, the Atlas super heavy would have a substantially expanded 8.4-meter first-stage central core powered by five engines. The expanded central core would be surrounded by four of the smaller first-stage cores used in the A5H+'s triple-stick configuration. Thus, the Atlas super-heavy launcher's first stage would be a five-stick configuration with 13 engines. The launcher's second stage would be similar to that of the A5H+ but would incorporate a lengthened payload shroud. Those changes would result in a vehicle capable of lifting 135 mt into LEO.

Six Alternative Launch Programs

CBO has constructed projections of the budgetary resources needed through 2017 to develop and procure launch vehicles that would support the return to the moon called for under the VSE. The projections are built for a total of six alternative launch programs—three that would use close-derivative launchers and three that would use super-heavy launchers—as follows:

- **The "pure Atlas-derived" alternative.**[8] This program would use the A5M+ launcher as the crew carrier and the A5H+ launcher as the cargo carrier.

- **The "pure Delta-derived" alternative.** This program would feature the D4M+ as the crew carrier and the D4H+ as the cargo carrier.

- **The "pure shuttle-derived" alternative.** This program would use the five-segment stick as the crew carrier and the Side-Mount as the cargo carrier.

- **The "pure Atlas-antecedent" alternative.** This program would use the A5M+ launcher as the crew carrier and the Atlas super heavy launcher as the cargo carrier.

- **The "pure Delta-antecedent" alternative.** This program would use the D4M+ as the crew carrier and the Delta super heavy launcher as the cargo carrier.

- **The "shuttle-derived super-heavy" alternative.** This program would use the five-segment stick as the crew carrier and the top-mounted, shuttle-derived super-heavy launcher as the cargo carrier. With the release of the President's budget for fiscal year 2007, it was also NASA's choice for VSE launch vehicles.

Programmatic Assumptions and Cost Comparisons

In order to construct budgetary projections for the alternatives described above, CBO needed to make a variety of "programmatic" assumptions, such as when launch vehicles would first be used, whether they would be used to lift cargo or a spacecraft and its crew, and how many test flights would be necessary before a launcher was

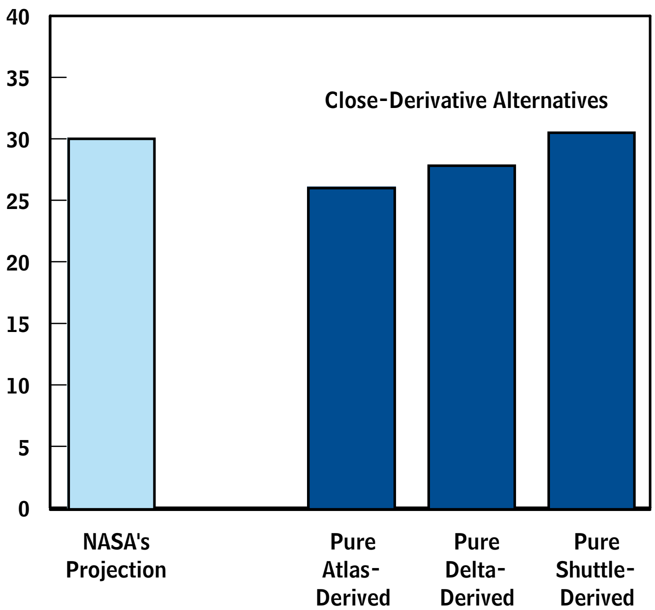
7. Although recently, NASA has announced that, instead of the SSMEs, it will be using RS-68 engines like those currently used on the Delta IV first stage.

8. The term "pure" means that both the crew carrier and the cargo carrier are derived from vehicles in the same (Atlas-, Delta-, or shuttle-derived) family of launchers.

Summary Figure 2.

Costs Through 2017 of Using Close-Derivative Launchers to Conduct Manned Lunar Missions Under the More Ambitious Schedule

(Billions of 2006 dollars)



Source: Congressional Budget Office.

Notes: NASA = National Aeronautics and Space Administration.

The more ambitious schedule initiates International Space Station support in 2012 and the first lunar mission in 2018.

The term "pure" means that both the crew carrier and the cargo carrier are derived from vehicles in the same family of launchers.

The term "close derivative" describes new launchers that retain a close pedigree to existing systems.

deemed ready for use. CBO used two sources for making those assumptions. First, to the extent that NASA's September 2005 Exploration Systems Architecture Study (ESAS) specified schedules and other program details, CBO used that study's assumptions—unless they were supplanted by materials the agency prepared to support the submission of the President's budget for 2007. In particular, justification materials supporting the 2007 budget indicate that NASA remains hopeful that it can meet the schedule outlined in the ESAS for conducting the first flight of the crew exploration vehicle, which is set for 2012, and the first manned lunar mission, which is planned for 2018. However, the agency recognizes that budget constraints might delay those events until 2014 and 2020, respectively. Therefore, CBO has constructed budgetary projections for the launch vehicle funding needed to execute both of those schedules. The programmatic assumptions that CBO made include the following:

- Certification of a launch vehicle—whether a crew carrier or a cargo carrier—for operational use would require three test or demonstration (test/demo) flights.

- Appropriations for hardware production and launch services would precede a launch by two years.

- The first operational flight of the CEV (which would be lifted into LEO by the crew carrier) would occur in either 2012 (under the more ambitious schedule) or 2014 (according to the less ambitious schedule). The first manned lunar mission would occur in either 2018 (the more ambitious schedule) or 2020 (the less ambitious schedule).

- Five ISS support flights per year would be conducted through 2016, beginning in either 2012 or 2014. Cumulative ISS support flights would therefore total 25 or 15. The launch vehicle for those flights would be the CEV launcher, regardless of whether or not the payload to the ISS included a crew.

- Two manned lunar missions would occur annually, beginning in either 2018 or 2020.

- No budgetary allowances for launch failure are made.

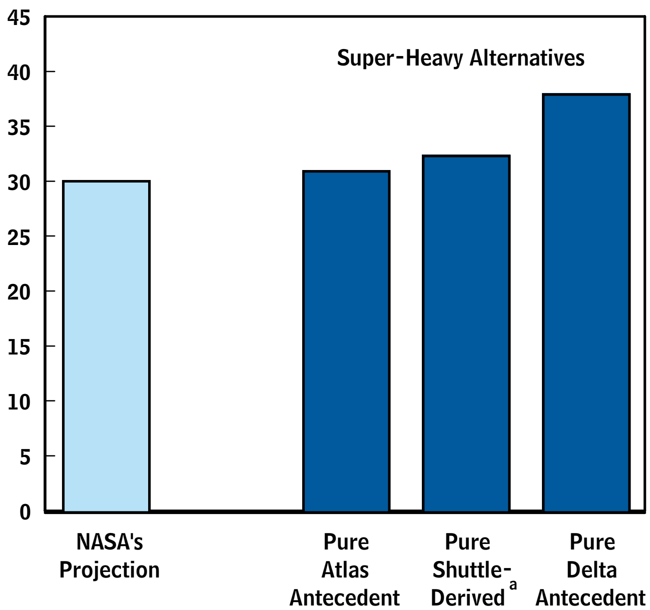
To execute the more ambitious schedule for returning humans to the moon, CBO estimates that total costs through 2017 for pursuing the three alternatives using close-derivative launch vehicles would range from about $26 billion for the pure Atlas-derived launch program to almost $31 billion for the pure shuttle-derived program (see Summary Figure 2). Executing the less ambitious schedule would cost $15 billion to $16 billion through 2017, CBO projects. In that case, the costs of executing the more ambitious schedule would simply be deferred to later years.

To execute the more ambitious schedule using the three alternatives that incorporate super-heavy launchers, CBO

Summary Figure 3.

Costs Through 2017 of Using Super-Heavy Launchers to Conduct Manned Lunar Missions Under the More Ambitious Schedule

(Billions of 2006 dollars)



Source: Congressional Budget Office.

Notes: NASA = National Aeronautics and Space Administration.

The more ambitious schedule initiates International Space Station support in 2012 and the first lunar mission in 2018.

Each alternative includes the close-derivative crew carrier associated with the indicated family. The term "pure" means that both the crew carrier and the cargo carrier are derived from vehicles in the same family of launchers.

The term "close derivative" describes new launchers that retain a close pedigree to existing systems.

a. NASA's choice of crew launch vehicle and cargo carrier as outlined in the President's budget for 2007.

estimates that costs through 2017 would range from about $31 billion to $38 billion (see Summary Figure 3). To execute the less ambitious schedule using super-heavy launchers, CBO estimates that costs through 2017 would range from about $20 billion to $26 billion. Again, executing the less ambitious schedule would simply defer costs to later years.

Both schedules imply a period when NASA could not support manned space flight with the proposed VSE vehicles after the retirement of the space shuttle in 2010. With the earlier, more ambitious schedule, the hiatus would be two years, and with the less ambitious schedule, it would be four years.

NASA's funding projections through 2017 to support the development and purchase of VSE launch vehicles total $30.1 billion. Through 2010, the projected amounts are about $1.0 billion annually. After 2010, annual amounts are about $3.5 billion. NASA's projection is constructed to support development and use of the shuttle-derived five-segment stick as the crew carrier and the similarly derived top-mounted super-heavy launcher as the cargo carrier—that is, the shuttle-derived super-heavy alternative considered by CBO. Through 2017, CBO's estimate of the budgetary resources needed to execute that alternative on the more ambitious schedule totals about $32 billion; CBO's estimate for executing the less ambitious schedule totals $20 billion.[9]

9. In May 2006, NASA announced that its design for the cargo carrier had evolved and now featured RS-68 engines in an expanded first stage rather than SSMEs. Using that new design for the cargo carrier, CBO's preliminary estimates of the total programmatic costs for the more aggressive schedule decreased to $30 billion and, on the less aggressive schedule, to $19 billion.

CHAPTER

1

Current Capabilities and Plans

With the exception of plans for manned space flight beyond low earth orbit (LEO)—which have been called for under the Bush Administration's Vision for Space Exploration (VSE)—sufficient capabilities exist through 2020 to meet projected needs of both U.S. commercial and governmental launching of unmanned payloads into space.[1] Those capabilities involve launching payloads that weigh less than 25 metric tons (mt), with the majority weighing less than 12 mt. Manned space flight beyond LEO, however, such as the return to the moon proposed under the VSE and now planned by the National Aeronautics and Space Administration (NASA), could require the development of the capability to launch payloads that weigh more than 100 mt. No launch vehicles presently exist that can handle payloads weighing more than about 25 mt. Thus, using current launch vehicles for a manned lunar mission would require that in excess of 100 mt of hardware and fuel be divided into multiple payloads that could be launched separately and then assembled into a functional whole in LEO before the mission departed for the moon.

The Vision for Space Exploration, which was issued as a Presidential directive on January 14, 2004, outlined goals for future exploration of the solar system using manned spacecraft. Among those goals was a proposal to return humans to the moon no later than 2020. The ultimate goal of resuming lunar missions would be to help enable eventual manned space flight beyond the moon—including to Mars. During the Apollo program (in effect from 1966 to 1972), manned space flight to the moon required the capability to launch about 140 mt into LEO, which was provided by a single Saturn V launcher.

1. Typical unmanned payloads consist of satellites designed to track weather or facilitate communications, conduct scientific research, or perform surveillance.

The details of the lunar missions being planned by NASA under the VSE could be more ambitious than those conducted under the Apollo program. In addition, NASA plans to use the crew exploration vehicle (CEV), the spacecraft that will be used to fly to and return from the moon and to service the International Space Station (ISS) after the retirement of the space shuttle in 2010. As will be discussed later, NASA has estimated that the net effect of those changes relative to Saturn/Apollo would increase the weight of a manned lunar mission by about 10 percent. Manned missions to Mars would, at a minimum, require launching payloads into LEO many times the weight required for lunar missions.

In this section of its analysis, the Congressional Budget Office (CBO) discusses projections that the Federal Aviation Administration (FAA) has made for commercial and governmental launches of payloads weighing less than 25 mt—that is, payloads not involving the VSE launch capabilities. Those projections indicate that currently existing launch capabilities should be sufficient to handle payloads weighing less than 25 mt through at least 2020. This chapter also discusses the issues that CBO considered in developing and assessing alternative launch systems that could potentially be used to execute the VSE. The specific alternatives that CBO developed are discussed in detail in Chapter 2.

Current Launch Capabilities and Projected Worldwide Demand Through 2020

Current estimates of worldwide launch capacity for payloads that weigh less than about 25 metric tons range from about 120 to 150 launches per year. Current projections of worldwide demand for launching such payloads

range between 70 and 80 launches a year (see Figure 1-1).[2] Projected capacity is an estimate of the maximum number of launches that existing launch pads and launch vehicle manufacturing facilities can support. Projected demand includes all launches now expected worldwide for either commercial or governmental purposes. Current projections indicate that maximum worldwide launch capacity for payloads of less than 25 mt will exceed demand by up to 100 percent for the foreseeable future.

Those projections of excess launch capacity may be underestimated, however. Data compiled by the FAA since 1993 indicate that actual launches of payloads—such as communications satellites—into geosynchronous orbit (GSO) range from about 60 percent to 86 percent of what has been forecast.[3] On average, actual launches conducted by the U.S. Air Force have been about 72 percent of its forecasts.[4] Projected launches exceed actual launches for a variety of reasons, including delays in the development and manufacture of the satellites scheduled for launch.

Worldwide demand for launches of payloads that weigh between 11.4 mt and 25 mt, referred to as heavy-launch demand by the FAA, is projected to be about 20 annually, much less than the estimated capacity (see Box 1-1 on page 4). Several current launch systems can accommodate the lifting of payloads at the upper end of that range (or beyond) into certain low earth orbits, including the space shuttle and the heavy-lift version of Boeing's Delta IV launcher.[5] Until its planned retirement in 2010, the space shuttle will be used almost exclusively to lift payloads associated with servicing and completing the construction of the ISS. Projected demand for Delta IV Heavy (D4H) launches is currently as high as two per year for U.S. governmental payloads. Launch vehicles with a maximum lift capability of between 11.4 mt and 20 mt include other versions of Boeing's Delta IV, versions of Lockheed Martin's Atlas V launcher, and a number of launchers manufactured abroad. The latter include the Ariane 5G used by the European Space Agency, the Chinese Long March 3B, and several variants of the Zenit and Proton launch systems now operated by the Single Economic Space.[6] The projected maximum capacity of those foreign systems, the majority of which can lift payloads no greater than about 18 mt, is somewhat greater than 40 launches annually.

The majority of the projected future worldwide demand for launches (about 72 percent) is associated with plans by governments, such as those of Russia, China, the United States, and members of the European Union, to place into orbit environmental-sensing satellites, other remote-sensing satellites (for example, synthetic aperture radars), and military-application satellites. With the exception of the period spanning 1997 to 2001—when launches of communications satellites from companies such as Iridium and Globalstar caused commercial demand to rise to about 42 percent of worldwide launches—this projection of continued dominance by

2. These projections are based on reports published by the Federal Aviation Administration and studies by the Futron Corporation, a company that the FAA and NASA use to project launch capacity and demand. See Federal Aviation Administration, Office of Commercial Space Transportation (AST) and the Commercial Space Transportation Advisory Committee, *2005 Commercial Space Transportation Forecasts* (May 2005); FAA and AST, *Commercial Space Transportation Quarterly Launch Report, 4th Quarter, 2004*; and Futron Corporation, *NASA ASCENT Study Final Report* (January 31, 2003). On April 11, 2005, Futron also provided data on projected launch vehicle rates directly to CBO. The projections displayed in this report include both capacity and demand for launching any payload expected to achieve earth orbit and exclude suborbital payloads (that is, payloads that do not achieve earth orbit). The capacity for space shuttle launches is assumed to be 10 annually. The FAA and Futron have published a May 2006 forecast for commercial launch demand that increases the potential number of such launches by seven in 2007 relative to the 2005 forecast. Beyond 2007, the 2005 and 2006 commercial launch forecasts differ very little.

3. Geosynchronous orbits, also known as geostationary orbits, are about 22,000 nautical miles (nm) high and allow satellites to hover over points on the equator. Other classes of orbits are also recognized. A low earth orbit is defined as one of a group of circular orbits that lies between the appreciable atmosphere (which is about 120 nm high) and the Van Allen radiation belt (which is about 1,000 nm high) and has an inclination to the equator of less than 60 degrees. Orbits with inclinations greater than 60 degrees are referred to as polar orbits. Also recognized are elliptical geosynchronous transfer orbits that are often used for transitions between LEOs and GSOs.

4. General T.S. Moorman (Ret.) and others, *Enabling Assured Space Access Study*, Booz Allen Hamilton (January 15, 2005), p. 17.

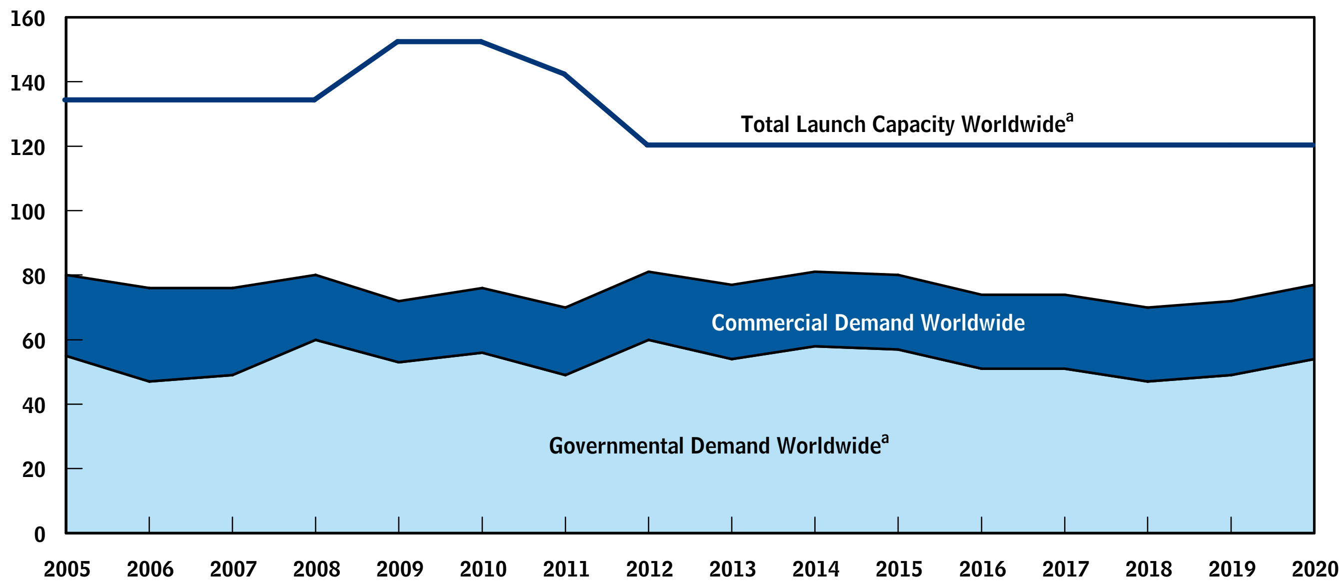
5. The Delta IV Heavy has flown only once and failed to place its payload into the correct orbit. Versions of the Angara rocket under development by the Khrunichev State Research and Production Space Center in Russia are being designed to lift up to 23 mt. A version of the Russian Proton launch vehicle can lift 20 to 21 mt.

6. The Single Economic Space consists of Russia, the Ukraine, Kazakhstan, and Belarus, which announced in the third quarter of 2004 that they intended to merge their space enterprises.

Figure 1-1.

Worldwide Capacity and Demand for Launch Services

(Number of launch vehicles)



Source: Congressional Budget Office based on data provided by the Federal Aviation Administration and the Futron Corporation.

Note: Capacity is the number of launches that existing infrastructure and production facilities can support if fully funded and staffed. Demand is either the number of launches required on historical launch manifests or current projections of future launch manifests. For a variety of reasons, therefore (because of delays in the availability of payloads, for instance), the number of actual launches usually ends up being less than the demand reflected on manifests.

a. Excludes the National Aeronautics and Space Administration's Vision for Space Exploration initiative.

governments for launch services is consistent with historical experience.

Although the number of satellites launched annually is projected to increase, the number of projected launches remains roughly constant.[7] That is because advances in electronics and composite materials are assumed to continue to reduce satellite mass, thereby allowing multiple satellites to be lifted into orbit during a single launch (known as multi-manifesting). That assumption also underlies the projection of the need for fewer launches of payloads that exceed 20 mt. (About 75 percent of payloads are lifted by launch vehicles that are not classified as heavy. At the upper end of the heavy range—that is, about 21 mt—projected demand through 2020 amounts to less than 3 percent of total demand.)

7. Futron has completed sensitivity analyses on assumptions that underlie these observations, but with the possible exception of a "breakout" of space tourism, the excess in space-launch capability is expected to continue.

If projections are restricted to payloads built by U.S. manufacturers and lifted into orbit using U.S. launch systems, supply exceeds demand through 2020, consistent with worldwide projections (see Figure 1-2 on page 5).[8] Both U.S. supply and demand make up about 40 percent of the respective worldwide annual projections through 2010. By 2020, however, U.S. demand is projected to fall to about 35 percent of worldwide launch demand. That occurs because the on-orbit lifetime of U.S. satellites is assumed to continue to improve, requiring fewer launches of replacement satellites. Demand for governmental and commercial launches in Asia is assumed to

8. Projections of U.S. launch capacity exclude the Sea Launch system operated by Boeing in partnership with RSC-Energia (based in Moscow), Kvaerner ASA (based in Oslo), and SDO Yuzhnoye/PO Yuzhmash (based in Dnepropetrovsk, Ukraine). Those projections also exclude the capacity provided using Proton and Angara launch vehicles at the Bakonur Cosmodrome in Kazakhstan of International Launch Services, a joint venture between Lockheed Martin and the Khrunichev State Research and Production Space Center in Russia.

Box 1-1.

Launch System Weight Classes and the Reference Orbit

The Federal Aviation Administration (FAA) distinguishes among launch vehicles on the basis of the maximum weight of payload that a given vehicle can place into orbit. The distinctions are as follows:

- Light = less than 2.3 metric tons (mt);
- Medium = 2.3 mt to 5.5 mt;
- Intermediate = 5.5 mt to 11.4 mt; and
- Heavy = greater than 11.4 mt.

The maximum payload that a launch vehicle can lift depends on both the launch site and the intended orbit. Therefore, to determine whether a given launcher is capable of lifting a light, medium, intermediate, or heavy payload, both the launch site and the orbit into which the payload is to be lifted must be specified. The FAA typically specifies a launch from Cape Canaveral, Fla., into a circular orbit that is 220 nautical miles (nm) in altitude at a 28.6 degree inclination to the equator. (A launch directly east from the Kennedy Space Center will result in an orbit inclined at the latitude of the center—28.6 degrees. The altitude of the orbit of the International Space Station, or ISS, is 220 nm.) Relative to that "reference" orbit, changes in altitude of plus or minus 100 nm would reduce or increase a given launch vehicle's maximum payload weight by about plus or minus 3 percent. Increasing the orbit's inclination to 56 degrees (the ISS's inclination) would reduce the launcher's maximum payload weight by about 8 percent.

increase as the economies of those countries, particularly China's and India's, continue to grow.

U.S. governmental demand for unmanned launches accounts for about 50 percent of total U.S. demand through 2020. That demand—about 94 percent of which is for payloads weighing less than 11.3 mt and none of which is for payloads exceeding 25 mt—is dominated by missions for the Department of Defense (DoD), NASA's unmanned earth and space science missions, and missions for the Department of Commerce, principally the launching of environmental-sensing satellites operated for weather forecasting and other purposes by the National Oceanic and Atmospheric Administration. DoD launches make up 63 percent of total governmental demand.

Launch Requirements for the Vision for Space Exploration

The only demand currently projected for launches into orbit of payloads that weigh more than 25 metric tons applies to the manned lunar missions now planned as part of the VSE program. The treatment here briefly compares and contrasts manned lunar missions conducted under the Apollo program and those planned under the VSE. The discussion also considers future missions to Mars.

Lunar Missions Under the Apollo Program

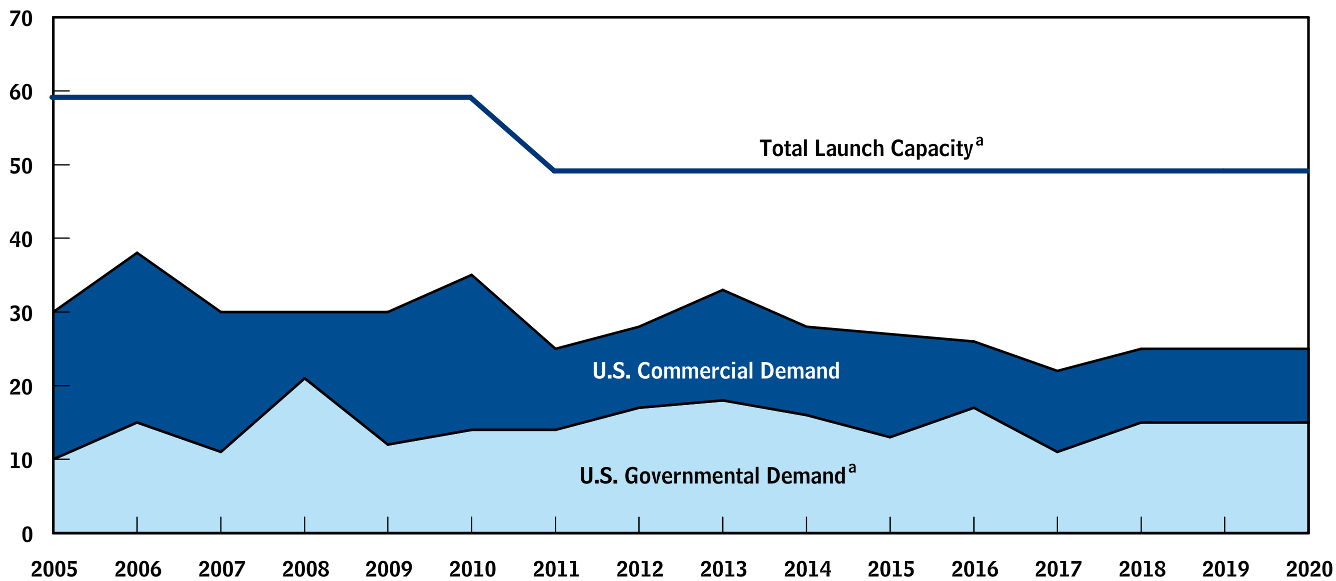
The Saturn V launcher was capable of lifting a payload of somewhat less than 140 mt into LEO.[9] That payload consisted of the Apollo three-man command-and-service module (CSM), the ascent and descent stages of the lunar module (LM), the lunar excursion module (LEM), and the third stage of the Saturn V, which was used both to reach orbit and to propel the CSM, LM, and LEM out of low earth orbit and into a lunar trajectory. The propellant used to travel to the moon, descend to and ascend from the moon's surface, and return to Earth made up about 75 percent of the 140 mt payload.

9. The payload of 140 metric tons is derived from weight data provided in Richard W. Orloff, *Apollo by the Numbers: A Statistical Reference*, NASA SP-2000-4029 (National Aeronautics and Space Administration, updated September 27, 2005), available at http://history.nasa.gov/SP-4029/SP-4029.htm. In that reference, 140 mt is the weight of the Apollo 17 command-and-service modules, the lunar module, the spacecraft/lunar module adapter, the instrument unit, and the S-IVB stage (the third stage of the Saturn V), including the fuel remaining in that stage needed to propel the Apollo command-and-service modules and lunar module from low earth orbit to the moon.

Figure 1-2.

Projections of U.S. Launch Capacity and Demand

(Number of launch vehicles)



Source: Congressional Budget Office based on data provided in May 2005 by the Federal Aviation Administration, the Futron Corporation, the U.S. Air Force, and the National Aeronautics and Space Administration (NASA).

Note: Capacity is the number of launches that the infrastructure and production facilities can support if fully manned and funded. Demand is either the number of launches required on historical launch manifests or current projections of future launch manifests. For a variety of reasons, therefore (because of delays in the availability of payloads, for instance), the number of actual launches usually ends up being less than the demand reflected on manifests.

a. Excludes NASA's Vision for Space Exploration initiative.

Lunar Missions Under the VSE

According to current estimates, implementing a return to the moon as NASA now plans to do under the VSE program would require that a payload of about 150 mt be lifted into LEO. NASA plans to use propellants similar to those used for the Saturn/Apollo program and engines with similar efficiencies. Thus, about the same amount of propellant per pound of payload that was lifted into LEO during the Saturn/Apollo missions would be necessary for NASA's planned return to the moon. NASA's current plans for the VSE indicate that it is considering an increase in the size of the crew relative to that of Apollo (six for the VSE versus three for Apollo)—implying the need for a larger spacecraft. NASA is also considering lunar landings farther from the moon's equator and lunar missions that would last longer than a few days (as was typical during the Apollo program). Those changes would require more fuel for both the descent to and ascent from the moon and a greater mass of other consumables for life support. NASA is also planning to use the spacecraft that will transport humans to and from the moon—the CEV—to transport crew and limited amounts of cargo to and from the International Space Station after retirement of the space shuttle in 2010. However, NASA plans to use lightweight composites and state-of-the-art miniaturized electronics in constructing the VSE spacecraft, as well as improved techniques for insulating stored cryogenic fuel that are designed to reduce leakage during travel to and from the moon. NASA has estimated that the net effect of all those changes might increase the mass lifted into LEO for a return to the moon by approximately 10 percent to somewhat more than 150 mt.[10]

10. That estimate was made by NASA during the summer of 2005. As NASA and its contractors continue to work on the designs for the hardware that will be used to conduct manned lunar missions, such weight estimates are likely to change.

Although in the Apollo program the payload for lunar exploration was lifted into LEO with one launch, NASA considered other options for the VSE program, most of which would require multiple launches. The use of multiple launches would mean that less-capable and individually cheaper launchers could be used. In particular, such a strategy could permit the use of existing launchers rather than require the development of a new launcher with lift capability exceeding 100 mt. Multiple launches also would mean that a single launch failure would not necessarily cause overall mission failure. Further, multiple launches could permit the crew to be lifted on a launcher designed to be highly reliable, while less reliable launchers were used to lift other elements of the payload (cargo) that would fly to the moon.

There are, however, potential drawbacks associated with using multiple launches. Multiple launches require time to execute (perhaps several months), during which subcomponents of the full payload, some likely containing cryogenic fuels, must remain in LEO. Notwithstanding improved techniques for insulating cryogenic fuels, on-orbit storage of such fuels for many months would be a challenge and would require that fuel in excess of the amounts actually burned would need to be lifted, thereby potentially increasing the total number of launches needed.[11] The subcomponents would also have to be assembled into a complete spacecraft on-orbit, potentially requiring the development of a capability for reliable and fully automated rendezvous and docking, which the United States has never demonstrated. Multiple launches could also complicate mission planning because a launch failure or the failure of on-orbit rendezvous and docking would render a payload subcomponent unusable, and which subcomponent might fail could not be predicted a priori. Thus, additional payload subcomponents might need to be kept ready for launch in order to ensure completion of a successful mission.

As will be discussed in Chapter 2, the program alternatives considered by CBO for meeting the launch needs of manned lunar missions would require two to four launches. NASA is currently planning to use two launches into LEO to execute a single mission to the moon: one using the crew carrier to lift the crew and a small amount of cargo (which cumulatively weigh about 26 mt) and a second using the cargo carrier to lift the rest of the cargo (including the lunar lander and the fuel needed to travel to and from the moon, which weigh about 125 mt).[12] The reasons NASA cites for that choice include crew safety and the avoidance of complexities associated with on-orbit assembly in LEO of more than two payloads.[13]

Future Mars Missions

In nine NASA studies completed between 1988 and 2000, estimates of the weight of the payload that would need to be lifted into LEO for a Mars mission ranged between 470 mt and 1,500 mt. The variation depended on the propulsion system used for the long journey

11. The use of noncryogenic propellants has also been proposed as a way to eliminate the problem of fuel leaking while it is stored in LEO. However, cryogenic propellants such as liquid hydrogen burned with liquid oxygen are the most efficient in terms of thrust produced per pound of fuel burned per unit of time. Although the use of noncryogenic propellants can reduce the weight of fuel tanks and engines, more of such propellants is needed to launch a given payload from LEO to the moon than is needed using cryogenic fuels. The latter effect usually dominates, implying that the use of noncryogenic propellants would require a heavier payload to be lifted from the Earth into LEO. For example, CBO estimates that the use of hydrazine and nitrogen tetroxide rather than liquid hydrogen and oxygen as the propellant for launching a mission to the moon from LEO would about double the weight of the propellant that must be lifted into LEO. The additional weight of cryogenic fuel that would need to be lifted to provide sufficient margin to accommodate leakage is less if the multiple launches needed to execute a mission can be achieved within approximately six-month periods of time. For instance, with passive cooling techniques, it is possible to limit leakage to under 4 percent per month, or less than 30 percent in a six-month period, according to a 1982 study conducted for NASA. Modern insulation further limits losses. See National Aeronautics and Space Administration, Contractor Report 3536, *Future Orbital Transfer Vehicle Technology Study*, vol. 2 (1982).

12. That choice was first presented with NASA's release of the draft results of its Exploration Systems Architecture Study (ESAS) in September 2005 and finalized in the ESAS *Final Report* in November 2005.

13. Arguments favoring the separation of crew and payload are implicit in the recommendations contained in "Long-Term: Future Directions for the U.S. in Space," Chapter 9.3 in *Columbia Accident Investigation Board Report*, vol. 1 (August 26, 2003). As discussed in Appendix B of this report, maximizing crew safety while maximizing launch vehicle lift capacity can be conflicting goals.

between LEO and Mars.[14] Therefore, the lightest Mars mission would require that a minimum of three to four times the mass of a lunar mission be launched into LEO.

NASA's plans for return missions to the moon avoid the complexities associated with on-orbit assembly that is dependent on more than two launches. However, such challenges for conducting a manned mission to Mars remain. Instead of developing a launch vehicle in at least the 400 mt class, which is not anticipated, capability for on-orbit assembly would be needed.[15] Assembling inert components in space can be either human-assisted or completely automated. If human-assisted, crew members could perform such operations on-orbit or control the assembly remotely. The United States has not demonstrated successful autonomous or remotely assisted assembly. Russia has demonstrated remotely assisted docking with its Progress resupply vehicle. NASA, however, has demonstrated only human-assisted, on-site assembly (for example, during construction of the International Space Station).

Unlike the mandated return to the moon, which has been slated for no later than 2020, the VSE states no specific schedule for a manned mission to Mars. Moreover, NASA's current planning through 2020 for manned space flight focuses on the funding and programs needed for returning humans to the moon. Consequently, this analysis, which examines launch needs through 2020, excludes consideration of launch capabilities and the associated technologies that may be needed to support human travel to Mars.

14. See National Aeronautics and Space Administration, *Launch Vehicle Capability Trade Study* (NASA briefing, 2003), which contains a comprehensive list of those nine studies. The lower-weight payloads correspond to the use of propulsion systems such as nuclear thermal rockets. Use of chemical propulsion of the same type that NASA now plans to use for the VSE lunar missions would require lifting payloads into LEO at the upper end of the range.

15. Assuming that the propulsion systems and design constraints are similar, CBO estimates that launching a payload three times larger than the maximum capacity of the Saturn V would require a launch vehicle about 1.4 times taller and wider than the Saturn V. Even if all engineering issues were surmountable, the infrastructure to build, transport, and launch such a large vehicle does not exist. The costs for those new facilities, ignoring the costs of the large vehicles themselves, would be substantial.

CHAPTER

2

Alternatives for Future NASA Manned Space-Exploration Capabilities

The Congressional Budget Office considered two sets of alternatives for resuming manned space flight to the moon: those that would use existing heavy-lift launch vehicles and those that would require developing new launch systems. The new launch systems assessed by CBO include close derivatives of existing systems as well as designs that represent major departures from existing launch vehicles. The close-derivative launch vehicles would require relatively modest changes to the designs of existing launch systems and, in the case of cargo carriers, would result in vehicles that could lift several times the weight of current payloads. The vehicles that would constitute major departures from existing vehicles—referred to as super heavies—would be able to lift payloads weighing 100 metric tons or more.

Existing Heavy-Lift Launch Systems

Existing U.S. heavy-lift launch systems considered by CBO include the following:

- The National Aeronautics and Space Administration's space shuttle;
- Boeing's Delta IV Heavy variant of the U.S. Air Force's family of evolved expendable launch vehicles; and
- The most capable variant of Lockheed Martin's Atlas V Medium EELV.[1]

Payload is an important factor in distinguishing among those systems. The D4H has a lift capacity of about 25 metric tons, the most capable variant of the Atlas V has a lift capacity of 20.5 mt, and the space shuttle can lift a payload weighing 18 mt.[2] The Saturn V rocket that was used for the original manned Apollo missions to the moon carried a much heavier payload than existing systems do, lifting about 140 mt into low earth orbit with a single launch (see Figure 2-1). Therefore, using today's U.S. launch systems would require six to eight launches to lift into LEO all of the mass necessary to execute a manned lunar mission.

Challenges Using the Space Shuttle

The challenges associated with ensuring safe and reliable operation of the space shuttle have led NASA to decide to retire the shuttle fleet in about 2010, after the International Space Station is completed. Therefore, using the shuttle to execute manned lunar missions would require that decision to be reversed. Based on its historical performance, the shuttle would be expected to have a launch failure rate of about 2 percent.[3] Because at least eight shuttle launches would be required to deliver about 140 mt into LEO, the probability that all those launches would succeed is about 87 percent. Thus, there is a significant chance—13 percent—that at least one payload would fail to reach LEO.

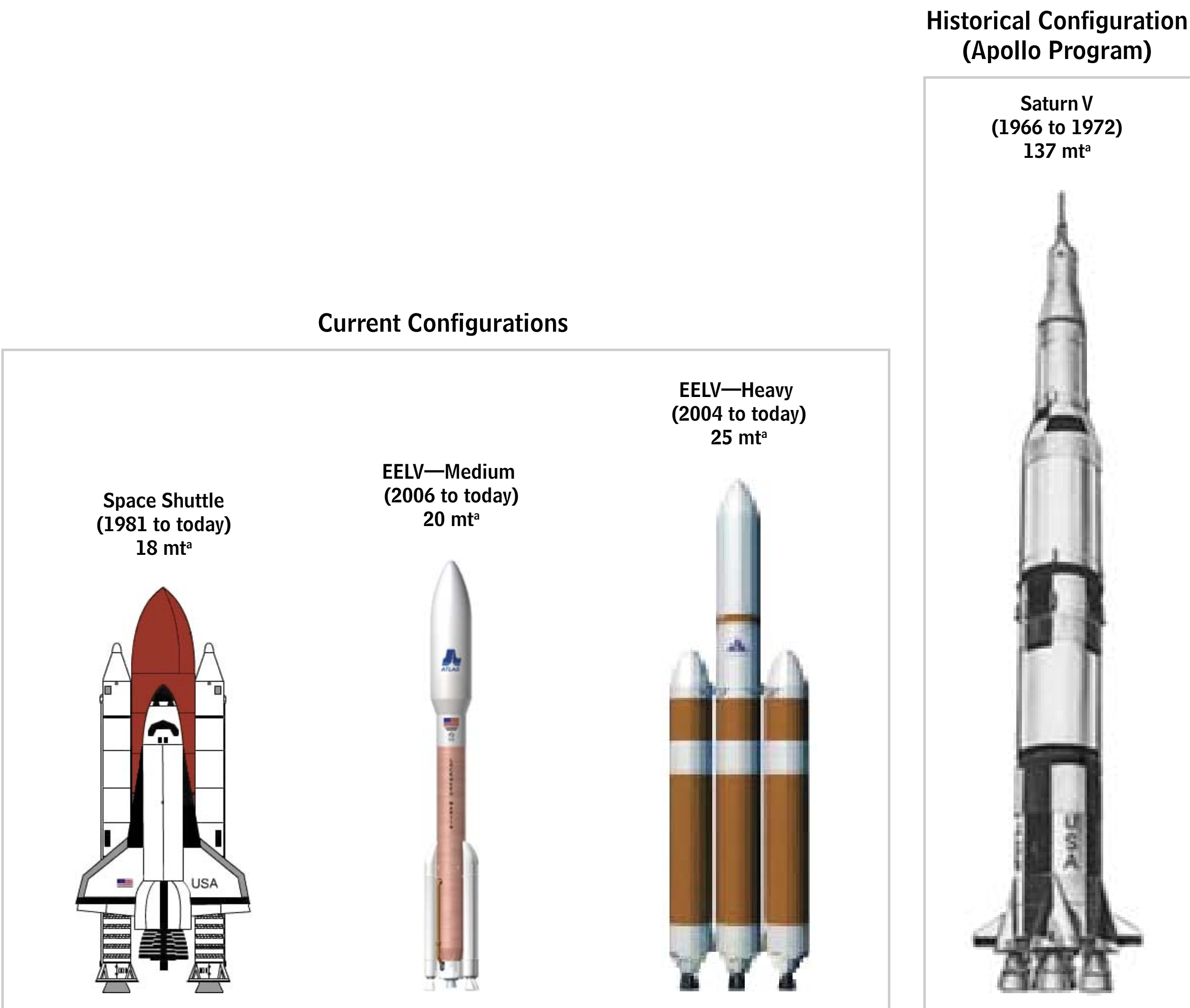
1. At the inception of the EELV program, the plan was to develop both Delta IV Heavy and Atlas V Heavy launchers capable of lifting about 25 mt into low earth orbit. Subsequently, the Department of Defense and Lockheed Martin agreed to forgo production of the A5H. Although the most capable version of the Atlas V is not designated a "heavy" launcher, its lift capacity places it in the heavy-lift launch category as defined by the Federal Aviation Administration.

2. Those payloads are assumed to be lifted into an orbit of 220 nautical miles in altitude inclined at 28.6 degrees. The combined weight of the space shuttle orbiter and the payload that is lifted into LEO is about 100 mt; however, the orbiter returns to Earth after delivering an 18 mt maximum payload into that reference orbit.

3. That rate attributes the loss of *Columbia* to launch failure because its breakup during reentry resulted from damage caused during liftoff by the shedding of foam insulation from the external tank.

Figure 2-1.

Existing and Historical U.S. Heavy-Lift Launch Vehicles



Source: Congressional Budget Office.

Note: Figures drawn to approximate scale; EELV = evolved expendable launch vehicle; mt = metric tons.

a. Metric tons of payload to a circular reference orbit of 220 nautical miles in altitude at a 28.6 degree inclination to the equator.

As has been noted previously, which launch might fail could not be predicted. Moreover, once a failure occurred, experience indicates that a long delay would ensue before shuttle operations resumed because of concerns regarding crew safety. As a result, it is likely that the failure of any of the eight space shuttle launches needed to assemble the 150 mt payload required for a manned lunar mission would mean overall mission failure.

Even if all of the launches were successful, simply executing eight space shuttle launches in rapid succession would be a challenge. During the quarter-century that the shuttle program has been in operation, its launch rate has reached eight missions annually only four times. Currently, NASA hopes to execute two lunar missions annually, which would require an unprecedented 16 shuttle launches per year. Moreover, as indicated previously, the need to limit on-orbit leakage of cryogenic fuels would most likely require that the lunar mission be assembled in

Table 2-1.

Characteristics of Existing U.S. Heavy-Lift Launch Vehicles

Characteristic	Space Shuttle	Delta IV Heavy	Atlas V	Saturn V (1969)
Payload Capacity to LEO (Metric tons)	18	25	20	137
Operational Launch Success Rate (Percent)	98.28[a]	[c]	100	100
Number of Launches	116	1	1	13 [f]
Design, Development, and Testing (Billions of 2006 dollars)	~40	3.5 [d]	2.0 [e]	31
Recurring Costs per Launch (Billions of 2006 dollars)	0.9	0.3	0.2	1.7
Recurring Costs per Pound of Payload (2006 dollars)	23,000/4,300 [b]	5,400	4,500	5,500

Source: Congressional Budget Office.

Note: LEO = low earth orbit. (For all launch systems, this orbit is a circular reference orbit 220 nautical miles in altitude at a 28.6 degree inclination to the equator.)

a. This statistic attributes the 2003 crash of the shuttle orbiter *Columbia* to launch failure.

b. The first figure is the cost per pound of the payload. The second is the cost per pound if the orbiter, whose inert mass is about 78 metric tons, is considered part of the payload.

c. The launch was not entirely successful because the test payload reached orbit but not the intended one.

d. Includes contractor and government investment for the entire family of launchers, an entirely new RS-68 engine, and launch-pad modifications at the Cape Kennedy and Vandenberg launch sites.

e. Includes contractor and government investment for the entire family of launchers and launch-pad modifications at the Cape Kennedy and Vandenberg launch sites.

f. The 13 launches consist of two unmanned flights, one manned mission to LEO, nine lunar-mission launches, and one Skylab launch.

LEO over a maximum of about six months. That requirement suggests the need for monthly shuttle launch rates twice those that have been achieved historically to conduct a single lunar mission.

Finally, because the reusable space shuttle returns to Earth and has to be refurbished before each launch, it is relatively expensive to use. Therefore, using the shuttle to lift a pound of payload into orbit costs about four times more than did using the Saturn V (see Table 2-1).

Challenges Using the Delta IV Heavy EELV

The launch reliability of systems such as the Delta IV class of vehicles should be similar to that of their Delta predecessors, as well as to that of the space shuttle (see Appendix A).[4] The number of launches required for the D4H to lift about 150 mt into LEO would be six, implying about a 10 percent chance that one payload would fail to reach orbit. Therefore, the use of the D4H to return humans to the moon would raise issues regarding overall mission success similar to those associated with using the space shuttle.

The Delta IV Heavy launch system was not designed for human space flight, however, which creates problems in complying with the safety standards that NASA has established for manned space flight. (At least one of the payloads lifted into LEO for a manned lunar mission would consist of the spacecraft that would travel to the moon with its crew.) Those problems include:

- A lack of redundant systems;
- Insufficient safety margins in the strength of the structures that compose the launcher;

4. When computed using a large sample of launches, there is no reason to expect the reliability of the Delta IV Heavy to be any better or worse than the demonstrated reliability of similar expendable launchers. However, the D4H has flown only once, and it failed to place its test payload into the intended orbit. The problem—cavitation in a fuel line, which could affect all Delta IVs—was discovered and fixed. The Delta IV Medium resumed flying on May 24, 2006.

- A lack of sensors and systems for monitoring the performance of the launch vehicle during flight—called health monitoring equipment—which could alert the crew to an impending failure and the need to execute a "launch escape"; and

- A need for modifications to the Delta launch pad to enable a crew to escape, if necessary, prior to launch.

A particular issue regarding the safety of manned space flight that is associated with the Delta IV Heavy launch vehicle is the trajectory it must follow as it lifts humans into orbit. The trajectory that enables the D4H to lift its full 25 mt payload tends to be especially steep, allowing the vehicle to ascend directly to high altitude. If the launcher developed a problem during ascent that required the crew to perform a launch escape by separating the crew from the booster, the ballistic trajectory on which the crew would descend to Earth would be similarly steep. The deceleration experienced by the crew during that steep descent into the atmosphere would exceed the safety limits specified by NASA, which are established to ensure that the crew does not suffer serious injury (see Appendix B). Therefore, using the D4H would require either that NASA's safety standards be relaxed or that the launcher fly a less direct trajectory. Use of a more gradual, or so-called depressed, trajectory would require more fuel to be expended per pound of payload lifted, reducing to under 20 mt the maximum weight of payload that the D4H could lift.

Challenges Using the Atlas V Medium EELV

The most capable version of the Atlas V Medium that is currently available can lift a 20.5 mt payload into LEO, which would require at least seven launches to execute a manned lunar mission. Therefore, its use to return humans to the moon would raise issues regarding overall mission success similar to those posed by either the space shuttle or the Delta IV Heavy. With some reduction in payload mass, the trajectory that the Atlas V followed could also be tailored to avoid the potential for crew injury during a launch abort. However, using the Atlas V would require resolution of the same problems related to redundancy, safety margin, health monitoring, and crew escape that are associated with the Delta IV Heavy launcher. Use of the A5M would further require that its Russian-made RD-180 engine be certified as acceptable for manned space flight. According to NASA staff, such certification would require the development of the capability for a U.S. supplier to manufacture and test the RD-180.

Close Derivatives of Existing Systems

CBO characterizes as "close derivatives" those new launch vehicles that retain a close pedigree to existing systems. Although those close derivatives may have the capacity to lift payloads two to four times heavier than existing launch vehicles, that increase in payload weight could be achieved by making major modifications to just a few components of an existing launch system. In this study, CBO analyzes the cost and performance of close-derivative launch vehicles that could be used to execute a manned lunar mission. The vehicles are similar to those considered by NASA and members of the U.S. space-launch industry, including Boeing, Lockheed Martin, and ATK Thiokol.[5] The close derivatives considered by CBO include modified versions of the space shuttle and its components, as well as modified versions of both the Atlas and Delta versions of the EELV. In all cases, the launchers used to lift the spacecraft and crew (called crew carriers) into LEO are distinct from the launchers (called cargo carriers) used to lift the remaining payload, such as the lunar lander and fuel needed to support flight to and from the moon.

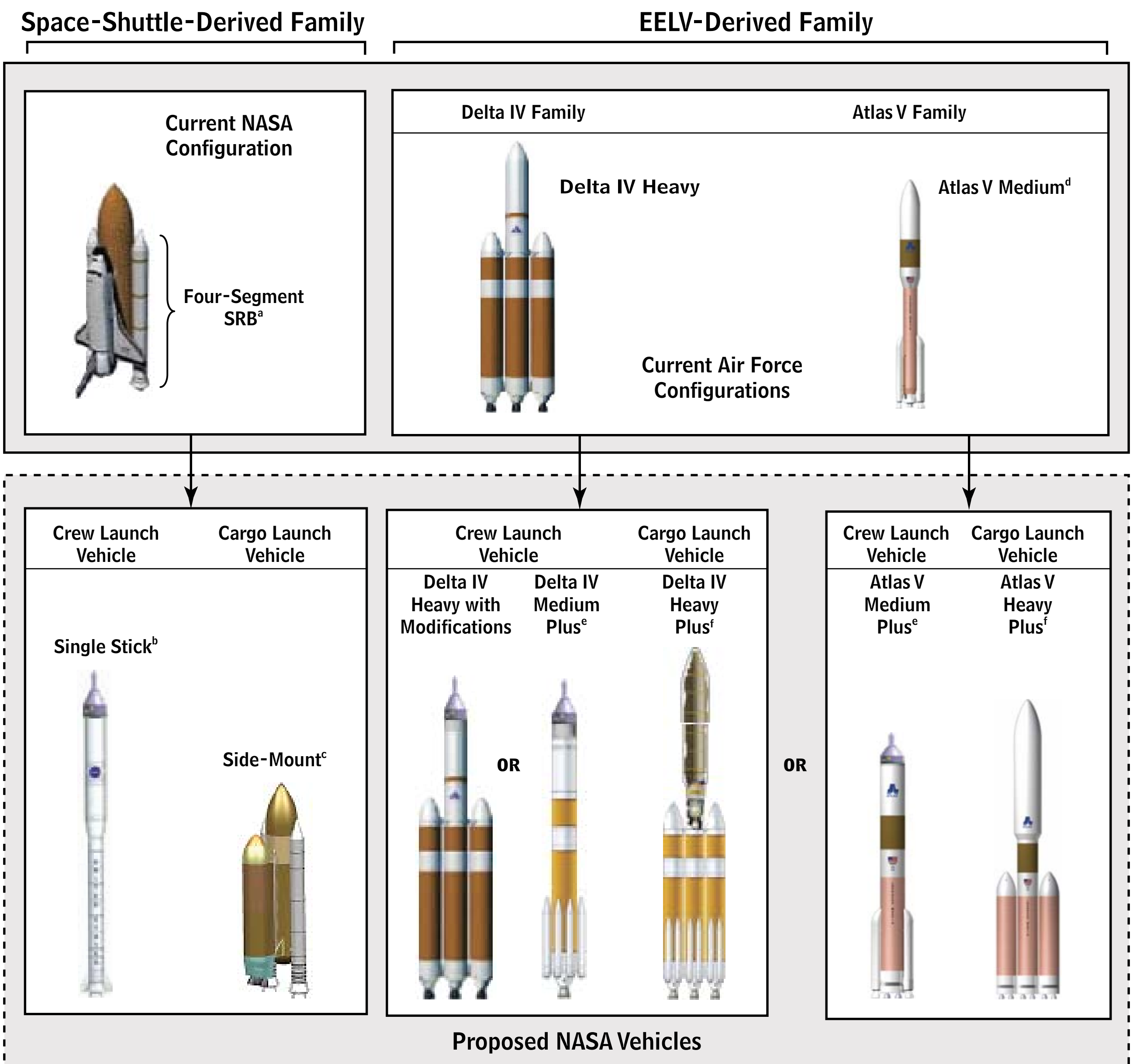
Shuttle-Derived Launch Vehicles

- **The Five-Segment "Stick" (crew carrier/lift capacity, 26 mt).** This launch vehicle is based on the four-segment solid rocket booster, a pair of which now help lift the space shuttle into orbit (see Figure 2-2). The main propulsion system for the shuttle is composed of three "sticks": two four-segment SRBs attached to the central external tank, or ET (the third stick). The ET carries the liquid hydrogen and liquid oxygen that fuel the space shuttle main engines housed in the rear portion of the orbiter (which is also attached to the ET). The SRBs are composed of individual cylindrical sections, each containing a casting of solid fuel. The single five-segment stick considered here would consist of five such sections, all of which would constitute the first stage of the rocket. A new second stage (with an independent liquid-fuel propulsion system) would be mounted on top of the SRB. The additional stage is needed to provide the capability to lift into LEO 26

5. The close-derivative launchers considered by CBO are based on information received from contractors and NASA from September 2004 through October 2005.

Figure 2-2.

Close-Derivative Launchers Considered by CBO and Their Antecedents



Source: Congressional Budget Office.

Note: Figures drawn to approximate scale; EELV = evolved expendable launch vehicle; SRB = solid rocket booster; NASA = National Aeronautics and Space Administration. The term "close derivative" describes those new launch vehicles that retain a close pedigree to existing systems. Figures may be family representatives.

a. The main propulsion system for the shuttle is composed of three "sticks": two four-segment SRBs attached to the central external tank (the third stick).

b. A single five-segment stick based on a four-segment SRB.

c. With cargo canister on side.

d. The A5 551 is the largest of the Atlas V medium-lift launchers. A design for a triple-stick Atlas V heavy-lift vehicle has completed Air Force review, but no production is planned.

e. The "Medium Plus" refers to an upgraded version of the medium (single-stick) branch of the respective EELV family of launchers.

f. The "Heavy Plus" refers to the triple-stick version of the medium plus branch of the respective EELV family of launchers.

Table 2-2.

Selected Characteristics of the Close-Derivative Launchers Considered by CBO

Alternative	Primary Mission	Payload to LEO (mt)	Launch-Abort Acceleration[b]
		Shuttle-Derived	
Five-Segment Stick[a]	Crew Carrier	26	10.6
Side-Mount	Cargo Carrier	77	c
		EELV-Derived	
Delta IV Heavy with Modifications (D4H with Mods)	Crew Carrier	21	18
Delta IV Medium Plus (D4M+)	Crew Carrier	18	18
Delta IV Heavy Plus (D4H+)	Cargo Carrier	40	c
Atlas V Medium Plus (A5M+)	Crew Carrier	24	16.5
Atlas V Heavy Plus (A5H+)	Cargo Carrier	74	c

Source: Congressional Budget Office based on data provided by the National Aeronautics and Space Administration, Boeing, Lockheed Martin, and ATK Thiokol.

Note: EELV = evolved expendable launch vehicle; LEO = low earth orbit (for all launch systems, this orbit is a circular reference orbit 220 nautical miles in altitude at a 28.6 degree inclination to the equator); mt = metric tons.

a. The main propulsion system for the shuttle is composed of three "sticks": two four-segment solid rocket boosters attached to the central external tank (the third stick).

b. If a launch fails, the maximum acceleration—expressed in multiples of gravity's acceleration—that a crew could experience in uncontrolled ballistic reentry.

c. Not a relevant characteristic for a cargo carrier.

mt. (NASA refers to that spacecraft as the crew exploration vehicle, or CEV.) As of September 2005, NASA's proposed solution for the crew carrier was a four-segment stick with a second stage propelled by modified versions of the space shuttle main engines. However, with the submission to the Congress of the President's fiscal year 2007 budget request, NASA changed that proposal to a five-segment stick using a second stage equipped with a variant of the less powerful J-2S engine—a modified version of the J-2 engine used on the second and third stages of the Saturn V. That combination of engines and booster would require that the engines in the CEV provide propulsion to attain the needed circular low earth "parking" orbit.

- **The Side-Mount (cargo carrier/lift capacity, 77 mt).** The Side-Mount would essentially consist of the space shuttle propulsion system with a cargo canister replacing the airplane-like orbiter. (Because it must house and protect a human crew and carry up to 18 mt of cargo to and from LEO, the 80-ton orbiter is relatively massive. Its structure, including its wings, must also withstand the heat and force of atmospheric reentry.) The cargo canister would be relatively light because it would be expendable. Therefore, the payload that the Side-Mount could lift into LEO would increase to about 77 mt (see Table 2-2).

EELV-Derived Launch Vehicles

- **The Delta IV Heavy with Modifications, or D4H with Mods (crew carrier/lift capacity, 21 mt).** The modifications that CBO considered would provide the component redundancy, structural safety margins, and health monitoring equipment required for manned flight. The D4H with mods, like the existing D4H, would be a three-stick launch vehicle with about three times the number of first-stage hardware components featured on the less capable, single-stick versions of the Delta IV. That additional hardware, however, also introduces additional opportunities for failure, making the D4H with mods less reliable than the shuttle-derived, single-stick launchers discussed previously.[6] The D4H with mods would be capable of lifting about 21 mt into a circular LEO.

6. That assessment is based on the contractor's estimates of the vehicles' reliability.

Table 2-3.

Comparison of the Costs of the Close-Derivative Launchers Considered by CBO

(Billions of 2006 dollars)

Alternative	Primary Mission	Nonrecurring Development Cost	Unit Recurring Cost (Five launchers per year)
		Shuttle-Derived	
Five-Segment Stick[a]	Crew Carrier	4.8	0.45
Side-Mount	Cargo Carrier	4.7	0.95
		EELV-Derived	
Delta IV Heavy with Modifications (D4H with Mods)	Crew Carrier	2.9	0.47
Delta IV Medium Plus (D4M+)	Crew Carrier	3.3	0.40
Delta IV Heavy Plus (D4H+)	Cargo Carrier	5.2	0.60
Atlas V Medium Plus (A5M+)	Crew Carrier	5.3	0.40
Atlas V Heavy Plus (A5H+)	Cargo Carrier	4.0	0.60

Source: Congressional Budget Office.

Note: EELV = evolved expendable launch vehicle.

a. The main propulsion system for the shuttle is composed of three "sticks": two four-segment solid rocket boosters attached to the central external tank (the third stick).

- **The Delta IV Medium Plus, or D4M+ (crew carrier/lift capacity, 18 mt).** Relative to the single-stick Delta IV Medium (D4M) EELV—which was developed for the U.S. Air Force and has executed several successful launches—the D4M+ would feature an enhanced first-stage core with six solid rocket boosters and an expanded second stage with additional engines. Those modifications would enable the D4M+ to lift about 18 mt into a circular LEO flying a depressed trajectory. Designed as a single-stick launcher, it would be more reliable than the D4H with mods.

- **The Delta IV Heavy Plus, or D4H+ (cargo carrier/lift capacity, 40 mt).** The Delta IV Heavy is built using three of the first-stage central cores featured on the Delta IV Medium. Similarly, the D4H+ would use three of the central cores of the D4M+, enabling it to lift roughly 40 mt of cargo into LEO.

- **The Atlas V Medium Plus, or A5M+ (crew carrier/lift capacity, 24 mt).** Developed for the Air Force, the Atlas V Medium has carried out several successful launches. Relative to the existing A5M launcher, the A5M+ would have a larger first-stage central core and an upgraded second stage providing the capability to lift about 20 mt into LEO. In addition, the A5M+ would incorporate the structural safety margins, component redundancy, and health monitoring equipment needed for manned space flight. Although the most capable version of the existing A5M can also lift 20 mt, it requires the use of five strap-on SRBs (attached to the first-stage central core) to do so. Because of its expanded first stage, the A5M+ would not need to use strap-on boosters, and its first stage would serve as the building block for a heavy-lift cargo carrier. The A5M+ would be capable of lifting about 24 mt into a circular LEO.

- **The Atlas V Heavy Plus, or A5H+ (cargo carrier/lift capacity, 74 mt).** The first stage of the Atlas V Medium Plus would serve as the basis for this three-stick vehicle. Relative to the A5M+, the A5H+ would feature additional engines in its second stage. It would have the capability to lift about 74 mt into LEO.

Comparisons of the Costs of the Close-Derivative Launchers

CBO's estimates for the costs of the launchers described above indicate the following (see Table 2-3):

- On a per-vehicle basis, recurring costs for the shuttle-derived crew carrier and the EELV-derived crew carriers would be about the same, within 10 percent.

- On a per-vehicle basis, recurring costs for the EELV-derived cargo carriers would be about one-third less than those for the shuttle-derived Side-Mount. Those lower costs reflect, in part, the potential for the sharing of fixed costs (such as for launch pads and production facilities) that is possible between EELV-derived vehicles and DoD's EELV program.[7] Such sharing is not possible with shuttle-derived vehicles because only NASA uses them. EELV-derived cargo carriers also have less lift capacity than the shuttle-derived cargo carrier: reduced performance implies lower costs for each individual launch vehicle. But, in the case of the EELV-derived D4H+, that reduced performance also means that more cargo carriers would have to be launched to conduct a lunar mission.

- Nonrecurring costs for the design, development, and testing of the EELV-derived launchers would be about the same, on average, as those for shuttle-derived launchers.

The methodology and assumptions on which these results are based are discussed in detail in Appendix E.

New Super-Heavy Launch Vehicles

The super-heavy launch vehicles considered by CBO are designed to lift payloads of 100 mt or more. In general, those prospective launchers would require physically significant and relatively expensive upgrades to many—and, in some cases, nearly all—of the major systems that make up existing launchers. Thus, developing super-heavy launchers would more than likely entail greater risks of cost growth and schedule slippage than would be the case with the close-derivative launchers discussed previously. A primary consideration would be the need to accommodate a larger number of engines in the first stage and, when present, the second stage.[8] (For depictions of the super-heavy launchers considered by CBO and comparisons of those vehicles to closely related existing launchers, see Figure 2-3. For greater detail, see Appendix D.) CBO considers super-heavy launch vehicles that use components of the space shuttle, as well as launchers that would represent new and much more capable designs that incorporate selected components (primarily engines) used on the current EELVs. CBO does not consider as an alternative rebuilding the Saturn V. Duplicating the infrastructure and engineering expertise needed to rebuild and reconfigure the Saturn V would probably make such an alternative unattractive when compared with alternatives that rely, at least in part, on the infrastructure and expertise associated with currently operational launchers.[9]

Super-Heavy Launchers That Use Shuttle Components

- **The Top-Mounted, Shuttle-Derived Super Heavy (cargo carrier/lift capacity, 125 mt).** In the President's budget for 2007, this cargo launch vehicle was identified as NASA's recommended solution for supporting manned lunar missions.[10] Because many of its major components would be drawn from the space shuttle, CBO refers to the vehicle as the shuttle-derived super heavy. Designed to be about the size of the Saturn V rocket, the vehicle would be able to lift a payload to LEO weighing about 125 mt (see Table 2-4). It would use five-segment solid rocket boosters (as opposed to the four-segment SRBs used on the shuttle). Two of those five-segment SRBs would be mounted on the sides of an elongated version of the shuttle's existing external tank, which would be modified to house five expendable versions of the existing (reusable) SSMEs. Because the vehicle has no second stage, the payload engine designated to continue powering the assembled lunar mission from low earth orbit would need to be burned twice: once to establish the needed circular low earth parking orbit; and a second, subsequent time to propel the assembled mission on a trajectory to the moon. A large cargo canister or shroud would be mounted on top of the ET/SRB assembly to house the payload.

7. The U.S. Air Force formally projects in its future manifests that it will fly about nine EELV flights annually, split roughly equally between the Delta IV and Atlas V. The annual number of EELV flights conducted recently, however, has been less than one-third of that projection.

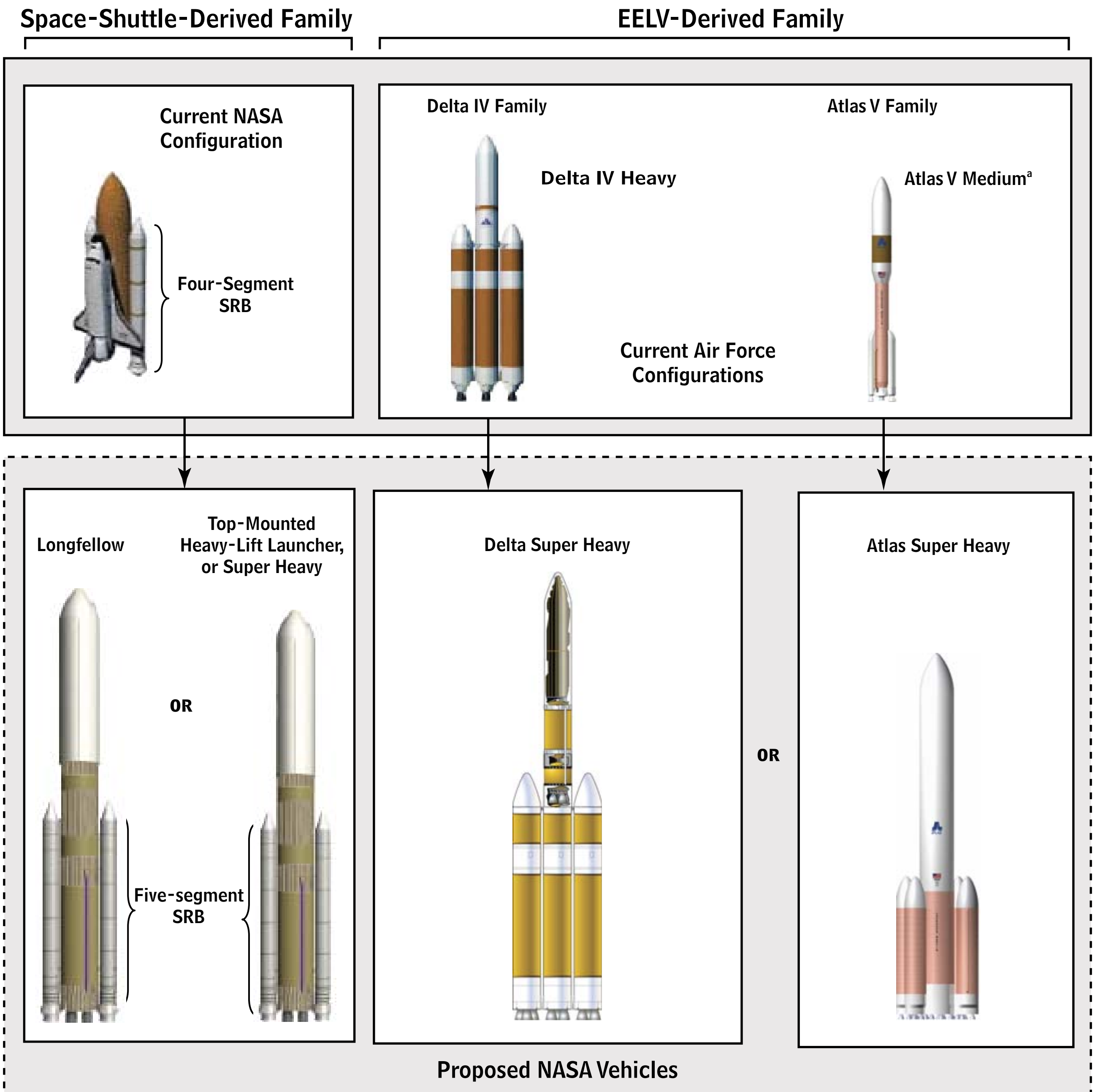
8. Builders of launch vehicles usually regard the development of new engines as the riskiest aspect of constructing new launchers. A risk-reduction step used by NASA and industry teams is to rely on proven engines (or only slight variations) but to build larger launchers to house more of them.

9. Ignoring the unavailability of parts and suppliers, reconfiguration might be necessary because the Saturn V does not meet current NASA safety standards (see Appendix B).

10. See Office of Management and Budget, *Budget of the United States Government, Fiscal Year 2007* (January 2006).

Figure 2-3.

Super-Heavy Launchers Considered by CBO as Cargo Launch Vehicles and Their Antecedents



Source: Congressional Budget Office.

Note: Figures drawn to approximate scale; EELV = evolved expendable launch vehicle; NASA = National Aeronautics and Space Administration; SRB = solid rocket booster.

a. The A5 551 is the largest of the Atlas V medium-lift launchers. A design for a triple-stick Atlas V heavy-lift vehicle has completed Air Force review, but no production is planned.

Table 2-4.

Selected Characteristics of the Super-Heavy Launchers Considered by CBO

Alternative	Primary Mission	Payload to LEO (mt)
Shuttle-Derived		
Longfellow	Cargo Carrier	108
Super Heavy	Cargo Carrier	125
EELV Antecedent		
Delta Super Heavy	Cargo Carrier	146
Atlas Super Heavy	Cargo Carrier	135

Source: Congressional Budget Office based on data provided by the National Aeronautics and Space Administration, Boeing, Lockheed Martin, and ATK Thiokol.

Note: EELV = evolved expendable launch vehicle; LEO = low earth orbit (for all launch systems, this orbit is a circular reference orbit 220 nautical miles in altitude at a 28.6 degree inclination to the equator); mt = metric tons.

- **The Longfellow (cargo carrier/lift capacity, 108 mt).** This launcher—proposed by an industry consortium that includes Boeing, Lockheed Martin, and ATK Thiokol—would resemble the shuttle-derived super heavy but with several different design aspects. Rather than expendable versions of SSMEs, the first stage of this launcher would rely on four of the RS-68 engines currently used on the Delta IV EELVs. It would also have a second stage powered by a single J-2S engine, atop which would be mounted a cargo canister. Because the Longfellow would be able to lift about 108 mt into LEO, overall its four RS-68 engines and single J-2S engine would provide less capability than the five SSMEs used on the shuttle-derived super heavy (see Table 2-4).[11]

11. In May 2006, NASA announced that it was changing the design of its super heavy to incorporate key features of both the shuttle-derived super heavy and the Longfellow. The new design for the 130 mt cargo carrier replaces the five SSMEs powering the vehicle's first stage with five of the RS-68 engines used on the first stage of the Longfellow. (Unlike the Longfellow, the newly designed cargo carrier would not have a powered second stage.) Five RS-68 engines would require more space under the tank, which in turn would require that the diameter of the first stage be larger than that of the existing ET. CBO lacks the information needed to prepare other than a preliminary estimate of the costs of this new cargo-carrier design.

Super-Heavy Launchers with EELV Antecedents

- **The Delta Super Heavy (cargo carrier/lift capacity, 146 mt).** The closest antecedent of this vehicle—proposed by Boeing—would be the existing Delta IV Heavy. The new launch vehicle, however, would incorporate many changes relative to the prospective Delta IV Heavy Plus. Those changes include the use of three expanded first-stage cores, each 8 meters in diameter and each equipped with four RS-68 engines. Thus, the three-core first stage of this launch vehicle would have 12 engines rather than the three-core, three-engine first stage of the existing D4H. The Delta super heavy would also have a larger second stage (8 meters in diameter) equipped with a single SSME. That SSME would be modified to start at high altitude (in contrast to the existing SSME, which is designed to start at sea level). In terms of physical dimensions, this launch vehicle would be the largest of the super heavies considered by CBO. It also would be capable of lifting the largest payload—about 146 mt—into LEO (see Table 2-4).

- **The Atlas Super Heavy (cargo carrier/lift capacity, 135 mt).** The closest antecedent of this vehicle—proposed by Lockheed Martin—would be the Atlas V Heavy Plus. Relative to that prospective launcher, the Atlas super heavy would have a substantially expanded 8.4-meter first-stage central core powered by five RD-180 engines (as opposed to the two that power the A5H+). The expanded central core would be surrounded by four of the smaller first-stage cores used in the A5H+'s triple-stick configuration. Thus, the first stage of the Atlas super heavy would consist of a five-stick configuration with 13 engines (see Figure 2-3). The launcher's second stage would be similar to that of the A5H+ but would incorporate a longer payload shroud. Those changes would result in a vehicle capable of lifting 135 mt into LEO (see Table 2-4). In physical dimensions, the Atlas super heavy would not need to be as large as the other super-heavy launchers considered by CBO. That difference is due primarily to the type of liquid fuel used for its first-stage engines: unlike the other prospective super-heavy launchers, which would use liquid oxygen and liquid hydrogen, the Atlas super heavy would consume liquid oxygen and a kerosene variant. The use of less-dense liquid hydrogen requires larger tanks, necessitating larger first-stage assemblages for the prospective super-heavy launchers that use space shuttle or Delta IV components.

Table 2-5.

Comparison of the Costs of the Super-Heavy Launchers Considered by CBO

(Billions of 2006 dollars)

Alternative	Nonrecurring Development Cost	Unit Recurring Cost (Two launchers per year)	Recurring Cost per Pound of Payload (Dollars per pound)
		Shuttle-Derived	
Longfellow	8.0	1.1	4,600
Super Heavy	8.9	1.3	4,700
		EELV Antecedent	
Delta Super Heavy	16.7	1.5	4,700
Atlas Super Heavy	9.0	1.2	4,100

Source: Congressional Budget Office.

Note: EELV = evolved expendable launch vehicle.

Comparisons of the Costs of Super-Heavy Launchers

The recurring launch costs of the super-heavy launchers considered by CBO range from $1.1 billion to $1.5 billion; their nonrecurring development costs range from $8 billion to nearly $17 billion (see Table 2-5).[12] By comparison, historical data indicate that the recurring launch costs of the Saturn V were about $1.7 billion and that its nonrecurring development costs were about $30 billion. The Saturn V's greater nonrecurring costs were attributable to the development of its engines and other associated technology—work that would not have to be repeated for the super-heavy launchers considered by CBO.

Unlike the case for close-derivative cargo launchers, the super-heavy launchers based on shuttle components are not necessarily more expensive than super-heavy launchers with EELV antecedents. The Atlas and Delta super-heavy launchers would be much larger than their EELV antecedents. Therefore, they could not as easily share the launch pads, manufacturing facilities, ground-support equipment, and other support facilities that the prospective close-derivative Atlas and Delta launchers would share with existing EELVs. The absence of the opportunity to share infrastructure is the primary reason that the Longfellow, Atlas, and shuttle-derived super-heavy launchers all have recurring and nonrecurring costs that are relatively similar.

Except for the Delta super heavy, nonrecurring costs for the super-heavy launchers would amount to about $9 billion. The Delta super heavy's nonrecurring costs would be significantly higher, primarily because of its size (and larger payload). Building and assembling the large-volume, triple-stick configuration of the Delta super heavy would require substantial modifications to existing manufacturing, integration, fuel storage and handling, and launch facilities—even if the shuttle launch pad was used for the Delta super heavy.[13] Accommodating those needs would cause nonrecurring costs for this launcher to be higher than corresponding costs for the other super-heavy launchers considered by CBO, which would make greater use of existing facilities that required fewer modifications (see Appendix E).

The Longfellow lifts the smallest payload into LEO of any of the prospective super-heavy launchers—108 mt. Thus, two Longfellow launchers would be needed to lift

12. CBO's preliminary estimates of the costs of NASA's latest design for the shuttle-derived super-heavy cargo carrier using five RS-68 engines indicate that the lower bound on those recurring costs could be about $1.0 billion and that the lower bound on nonrecurring costs could be about $7.4 billion.

13. Details of the infrastructure requirements and their relatively high expense were provided to CBO on August 5, 2005, during discussions with members of Boeing's Launch Services Division in Huntington Beach, Calif.

the cargo associated with a single manned lunar mission, basically negating its lower per-launch cost.[14]

According to CBO's estimates, the unit cost of the Atlas super heavy would be 10 percent less than that of the shuttle-derived super heavy.[15] Nonetheless, some observers might argue that the shuttle-derived launcher would be more cost-effective than the Atlas. Relative to the shuttle-derived super heavy, the first stage of the Atlas super heavy would be more complex because of its larger number of engines (15 versus seven) and sticks (five versus three). Generally, greater complexity implies reduced reliability (because of greater opportunities for potential failure).[16,17] If the Atlas failed more often than the shuttle-derived super heavy, its use might be more expensive overall because of the need for additional launches to compensate for failures.

Program Cost Comparisons

In this section, CBO provides projections for the funding that NASA would need for launch vehicle development and procurement to execute manned lunar missions using the alternative crew and cargo launchers described previously. Those CBO projections are compared with NASA's current projection of the funding it estimates will be needed through 2017 to develop and buy launch vehicles capable of supporting both flight to the International Space Station and manned lunar missions.

To generate those projections, CBO needed to make a variety of "programmatic" assumptions, such as when the vehicles would first be used to launch either cargo or a spacecraft and its crew and how many test flights would be necessary before a launch vehicle was deemed ready for use. CBO used two sources for building those assumptions. First, to the extent that the September 2005 Exploration Systems Architecture Study documented the programmatic assumptions NASA is using, CBO's projections are built on those assumptions—unless they have been subsequently superseded by materials the agency prepared for the President's budget. In particular, justification materials provided for the 2007 budget indicate that NASA remains hopeful it can meet the schedule outlined in the ESAS for conducting the first flight of the CEV in 2012 and the first manned lunar mission in 2018. However, the agency recognizes that budget constraints might delay those events until 2014 and 2020, respectively. Therefore, CBO has constructed budgetary projections for launch vehicle funding needed to execute both of those schedules. The programmatic assumptions that CBO made include the following:

- Certification of a launch vehicle—whether a crew carrier or a cargo carrier—for operational use requires three test or demonstration (test/demo) flights.
- Appropriations for hardware production and launch services precede a launch by two years.
- The first operational flight of the CEV (carried aloft by the crew carrier) occurs in either 2012 (the more ambitious schedule) or 2014 (the less ambitious schedule). The first manned lunar mission occurs in either 2018 (the more ambitious schedule) or 2020 (the less ambitious schedule).
- Five ISS support flights per year are conducted through 2016 beginning in either 2012 or 2014.[18] Regardless of whether the payload to the ISS includes a crew, the launcher for those flights will be the crew

14. Based in part on the *Columbia Accident Investigation Board Report* and NASA's decision to separate cargo and crew launches, CBO did not consider a case in which one Longfellow would launch cargo and a second would launch the remaining cargo, as well as the lunar spacecraft and its crew.

15. CBO's preliminary estimate of the costs of NASA's latest design for the shuttle-derived super heavy, which would use five RS-68 engines instead of SSMEs, suggests that this relationship could be reversed: rather than 10 percent lower, the unit cost of the Atlas super-heavy cargo carrier could be about 20 percent higher.

16. Reliability calculations are complex, involving a number of trade-offs. On the one hand, more engines and sticks imply the need for more tanks, valves, sensors, and moving parts, all of which present more failure modes. On the other hand, with enough engines, if one failed to ignite (one of the most common failure modes for engines), the remaining engines might still be able to deliver a payload into its intended orbit.

17. The first stage of the Soviet N-1 moon rocket had 30 engines. All four test flights of that rocket ended in failure before separation of the first stage could be completed.

18. NASA also supports the ISS with funds in another account called the ISS Cargo and Crew Services (ISS CCS) project. This account funds both purchases of launches from foreign providers (in particular, Russia) and development of U.S. commercial launch services to LEO. In NASA's budget projections through 2017, which were prepared earlier this year, the agency assumes that its crew carrier will be used for five ISS support flights annually, with the new ISS CCS project providing one additional support flight to the ISS annually.

Table 2-6.

Cargo Launches Needed to Execute a Manned Lunar Mission with the Alternative Cargo Launchers Considered by CBO

Alternative	Payload to LEO (mt)	Cargo Launches per Lunar Mission	Maximum Cargo Payload per Lunar Mission (mt)[a]
		Shuttle-Derived	
Side-Mount	77	2	154
Longfellow	108	2	216
Super Heavy	125	1	125
		EELV Antecedent	
Delta IV Heavy Plus (D4H+)	40	3	120
Atlas V Heavy Plus (A5H+)	74	2	148
Delta Super Heavy	146	1	146
Atlas Super Heavy	135	1	135

Source: Congressional Budget Office based on data provided by Boeing, Lockheed Martin, and ATK Thiokol.

Note: EELV = evolved expendable launch vehicle; LEO = low earth orbit (for all launch systems, this orbit is a circular reference orbit 220 nautical miles in altitude at a 28.6 degree inclination to the equator); mt = metric tons.

a. Does not include 18 to 28 mt delivered to LEO by a separate launch of the crew carrier.

launch vehicle. With the retirement of the space shuttle projected to occur in 2010, this assumption implies a hiatus in manned space flight of two to four years.

- Two manned lunar missions occur annually, beginning in either 2018 or 2020.

- No budgetary allowances are made for launch failure.

The more ambitious schedule would require that 29 crew carriers be purchased to conduct operational launches through 2017.[19] Twenty-five of those vehicles would support ISS missions, and four would be designated for lunar missions. Executing the more ambitious schedule would require purchasing four to 12 cargo carriers through 2017 to conduct lunar missions starting in 2018. The range in the number of needed cargo carriers reflects the differing number of launches associated with each of the alternatives that CBO considered (see Table 2-6).

The less ambitious schedule implies that 15 crew carriers would be purchased through 2017 to conduct operational launches. All of those launchers would be used for ISS support missions. Executing the less ambitious schedule would not require cargo carriers to be purchased through 2017 to conduct operational launches, however.

The Vision for Space Exploration Initiative: Projected Funding for Launch Vehicles

Through 2017, NASA has projected the funding that it anticipates will be needed to develop and purchase launch vehicles to conduct missions to the ISS and to the moon. Four accounts are directly related to VSE launch vehicles under what the agency calls its Constellation Systems Program, as follows:

- Crew Launch Vehicle. This account also supports the delivery of crew and cargo to the ISS using the five-segment launcher.

- Heavy-Lift Launch Vehicle (the cargo carrier).

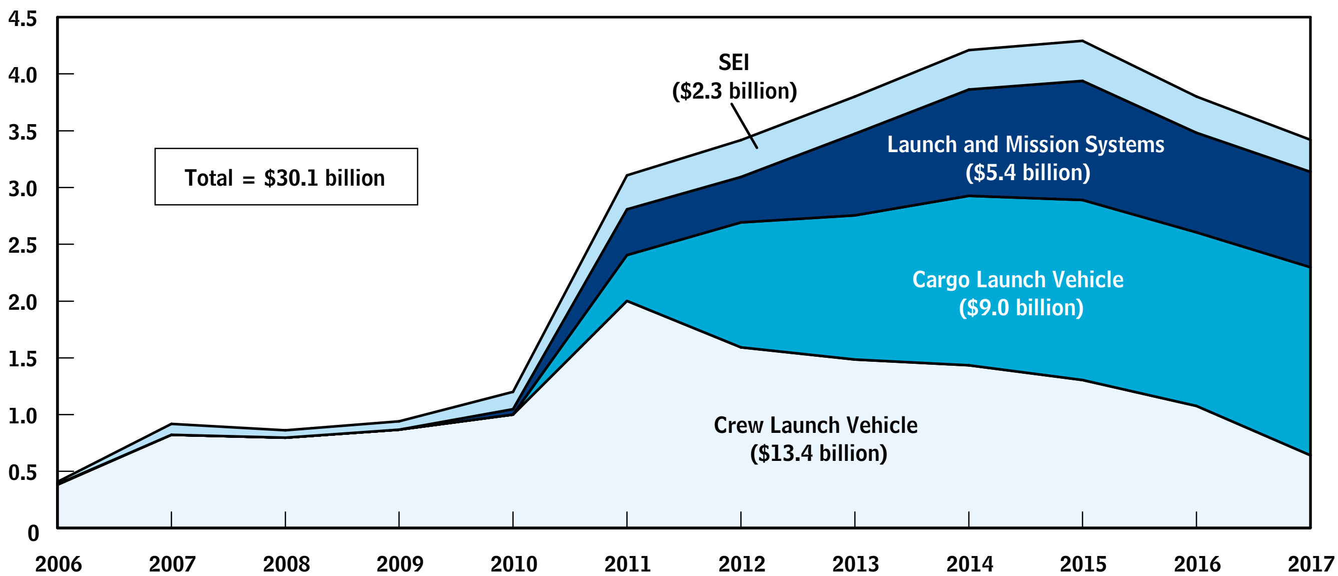
- Launch and Mission Systems (L&MS). This account covers processing, launch operations, and research and development of facilities, ground equipment, control systems, and communications networks for the crew launch vehicle, the cargo carrier, and the CEV. NASA

19. An operational launch is executed in order to conduct a mission to the space station or to the moon. CBO distinguishes those launches from the test launches conducted in order to assure that a newly developed launcher is ready for operational use. The number of test launches conducted through 2017 under any given alternative is the same for either the more ambitious or less ambitious schedule.

Figure 2-4.

NASA's Projected Funding for VSE Launch Vehicles Through 2017

(Billions of 2006 dollars)



Source: Congressional Budget Office based on the President's budget for fiscal year 2007.

Note: NASA = National Aeronautics and Space Administration; SEI = system engineering and integration; VSE = Vision for Space Exploration.

budget materials available to CBO do not specify how much L&MS funding will be allocated to the CEV and how much to the launchers. Therefore, CBO assumes that, through 2010, L&MS funding is solely associated with the CEV. After 2010, two-thirds of the funding is assumed to be associated with crew and cargo launchers.

- System Engineering and Integration (SEI). This account funds activities that support all aspects of the Constellation Systems Program. The NASA budget-materials available to CBO do not specify how much SEI funding will be allocated to support development and operational launches of the crew and cargo carriers. Therefore, CBO assumes that the fraction of SEI funding allocated to support launch vehicles will be equal to the fraction of funding for the Constellation Systems Program (less SEI) composed of the three launch vehicle accounts listed immediately above.

Through 2017, NASA's projections for cumulative funding in those four accounts, which is slated to support the development and purchase of VSE launch vehicles, total $30.1 billion. Through 2010, the projected amounts are about $1.0 billion annually. After 2010, annual amounts are about $3.5 billion (see Figure 2-4). NASA's projection is constructed to support the development and use of the five-segment stick as the crew carrier and the shuttle-derived super-heavy launcher as the cargo carrier.

Comparisons of Program Costs Using Close-Derivative Launchers

CBO has constructed budgetary projections through 2017 for three alternative launch programs that would use close-derivative launchers, as follows:

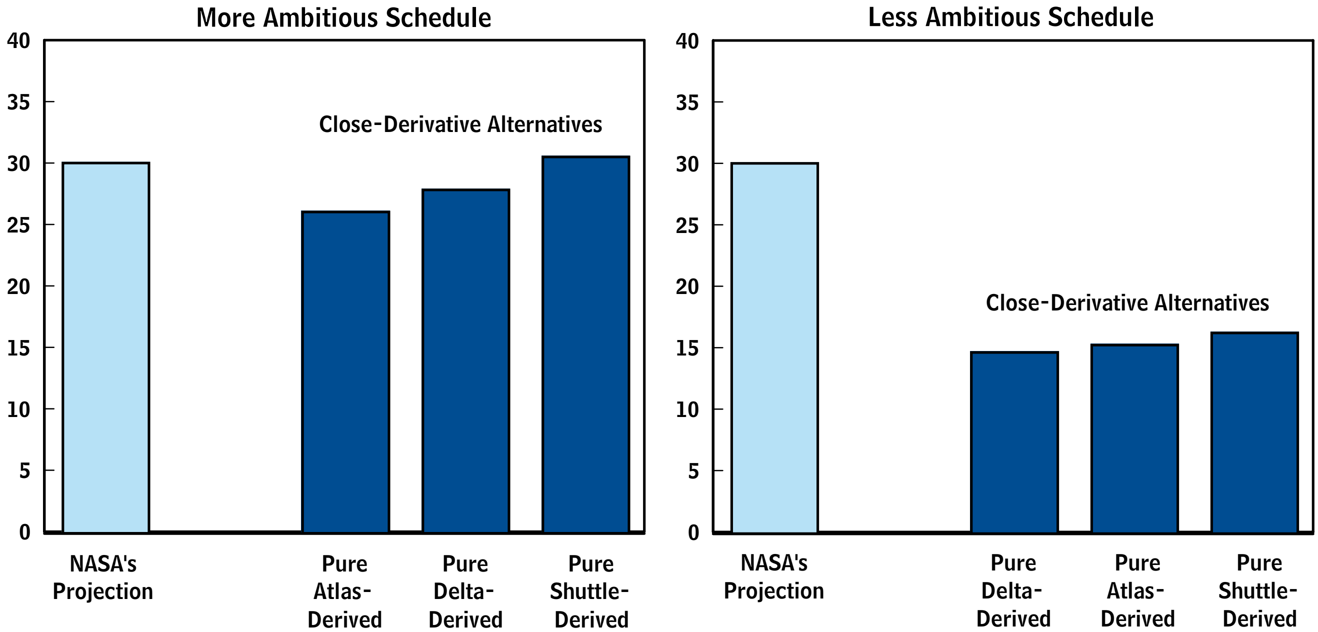
- **The "pure Atlas-derived" alternative.** This program would use the A5M+ launcher as the crew carrier and the A5H+ launcher as the cargo carrier.

- **The "pure Delta-derived" alternative.** This program would feature the D4M+ with mods as the crew carrier and the D4H+ as the cargo carrier.

Figure 2-5.

Costs Through 2017 of Using Close-Derivative Launchers to Conduct Manned Lunar Missions

(Billions of 2006 dollars)



Source: Congressional Budget Office.

Notes: NASA = National Aeronautics and Space Administration.

The more ambitious schedule initiates International Space Station support in 2012 and the first lunar mission in 2018. The less ambitious schedule initiates International Space Station support in 2014 and the first lunar mission in 2020.

The term "pure" means that both the crew carrier and the cargo carrier are derived from vehicles in the same family of launchers. The term "close derivative" describes new launchers that retain a close pedigree to existing systems.

- **The "pure shuttle-derived" alternative.** This program would use the five-segment stick as the crew carrier and the Side-Mount as the cargo carrier.

The above three alternative programs do not constitute a complete set of alternatives that could be pursued using the four close-derivative crew carriers and three close-derivative cargo carriers described previously. CBO has chosen to analyze this subset in order to limit the number of budgetary projections it built to a manageable number while still illustrating the differences in costs associated with pursuing EELV-derived or shuttle-derived programs.

To execute the more ambitious schedule for returning humans to the moon, CBO estimates that total costs through 2017 for pursuing the three alternatives it considered using close-derivative launchers would range from about $26 billion for the pure Atlas-derived launch program to almost $31 billion for the pure shuttle-derived program (see Figure 2-5). Executing the less ambitious schedule would cost $15 billion for the pure Delta-derived program to $16 billion for the pure shuttle-derived program through 2017, CBO estimates.

Comparisons of Program Costs Using Super-Heavy Launchers

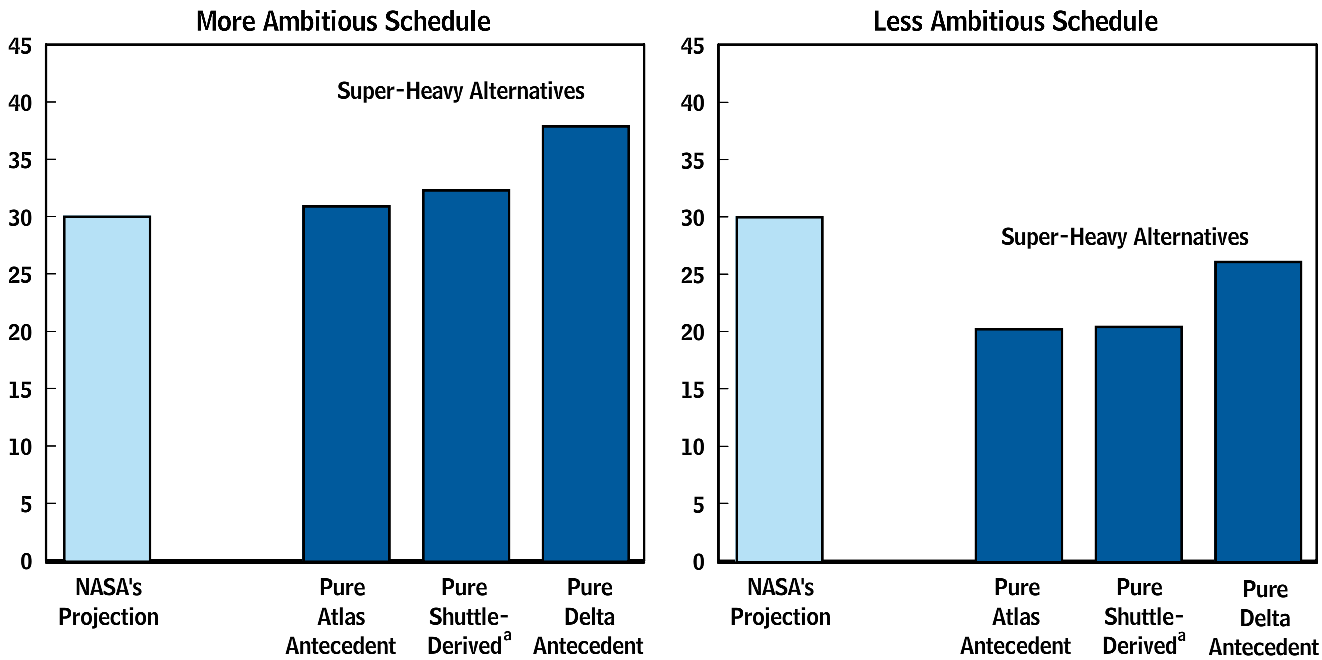
CBO has constructed budgetary projections through 2017 for three alternative launch programs that would use new super-heavy launchers, as follows:

- **The "pure Atlas-antecedent" alternative.** This program would use the A5M+ launcher as the crew carrier and the Atlas super-heavy launcher as the cargo carrier.

Figure 2-6.

Costs Through 2017 of Using Super-Heavy Launchers to Conduct Manned Lunar Missions

(Billions of 2006 dollars)



Source: Congressional Budget Office.

Notes: NASA = National Aeronautics and Space Administration.

The more ambitious schedule initiates International Space Station support in 2012 and the first lunar mission in 2018. The less ambitious schedule initiates International Space Station support in 2014 and the first lunar mission in 2020.

Each alternative includes the close-derivative crew carrier associated with the indicated family. The term "pure" means that both the crew carrier and the cargo carrier are derived from vehicles in the same family of launchers.

The term "close derivative" describes new launchers that retain a close pedigree to existing systems.

a. NASA's choice of crew launch vehicle and cargo carrier as outlined in the President's budget for 2007.

- **The "pure Delta-antecedent" alternative.** This program would use the D4M+ as the crew carrier and the Delta super-heavy launcher as the cargo carrier.

- **The "shuttle-derived super-heavy" alternative.** This program would use the five-segment stick as the crew carrier and the top-mounted, shuttle-derived super-heavy launcher as the cargo carrier. Upon submission of the 2007 budget, this was NASA's choice for VSE launch vehicles.[20]

To implement the more ambitious schedule using super-heavy launchers, CBO estimates that costs through 2017 would range from $31 billion to $38 billion (see Figure 2-6). CBO's estimates indicate that using NASA's choice of launch vehicles to execute the more ambitious schedule would cost about $2 billion more than the funding contained in NASA's budget projection through 2017.[21]

20. See Office of Management and Budget, *Budget of the United States Government, Fiscal Year 2007.*

21. CBO's preliminary estimate for the costs of NASA's latest design for the shuttle-derived super-heavy cargo carrier, which uses five RS-68 engines, indicates that programmatic costs for the more ambitious schedule could be about $30 billion, essentially the same amount contained in NASA's future funding projection.

To execute the less ambitious schedule using super-heavy launchers, CBO estimates that costs through 2017 would range from $20 billion to $26 billion. CBO's estimates in this case indicate that using NASA's choice of launch vehicles would cost about $10 billion less through 2017 than the funding contained in NASA's budget projections.[22] (However, given the risks inherent in the designs of the crew and cargo launchers chosen by NASA, CBO's estimates could be low; see Box 2-1.) That savings comes from reducing the number of ISS support missions from 25 to 15 and delaying procurements for four lunar missions beyond 2017.

22. CBO's preliminary estimate for the costs of NASA's latest design for the shuttle-derived super-heavy cargo carrier, which uses five RS-68 engines, indicates that programmatic costs for the less ambitious schedule could be about $19 billion, which is about $11 billion less through 2017 than NASA's future funding projection.

Box 2-1.

Risks Associated with Developing and Producing NASA's Launch Vehicle Choices

The National Aeronautics and Space Administration (NASA) has acknowledged that its choice of launch vehicles, particularly the five-segment stick proposed by the agency as a crew carrier, presents a number of risks.[1] Such risks could cause actual costs to exceed, perhaps substantially, estimates made by the Congressional Budget Office (CBO). The risks cited by NASA personnel relate to the following functions:

- **Stability control.** A launch vehicle's stability—that is, its resistance to deviation from its intended flight path—is related to its ratio of height to width; the higher the ratio, the greater the potential for problems with stability. Launcher designs usually attempt to maintain a height-to-width ratio that is no greater than 15:1; but, the five-segment stick will have a height-to-width ratio of 18:1. Thus, NASA expects that maintaining stability control of the five-segment stick will present a greater challenge than that posed by existing launch vehicles.

- **A large second stage powered by a modified engine.** Since the 1960s, the largest second stages have had dry weights (that is, weight that does not consist of fuel) of about 4 metric tons (mt) or less. By contrast, the second stage of the five-segment stick will weigh about 10 mt. (That additional weight is a contributor to the five-segment stick's relatively large height-to-width ratio.) The second stage will be powered by an updated version of the J-2S engine, which was developed at the end of the Apollo program.

- **Structural integrity of the five-segment solid rocket booster.** The crew carrier's five-segment solid rocket booster must support the weight of both the second stage and the crew exploration vehicle during powered flight. NASA expects that the structural safety margins incorporated in the design of the four-segment sticks used for the space shuttle will suffice for the five-segment stick, even though the four-segment stick was designed for substantially different loads and stresses. However, the testing needed to verify that expectation remains to be done.

- **Organizing and executing the construction of a launch vehicle rated for manned space flight.** NASA last oversaw such an effort more than 20 years ago with the development and testing of the space shuttle.

Since NASA's publication of the Exploration Systems Architecture Study (ESAS), the crew carrier has evolved from a four-segment stick with a second stage powered by a space shuttle main engine (SSME) to a five-segment stick with a variant of the J-2S engine, which has less lift capability.

Evolution of the cargo carrier design has also begun. Recently, NASA announced that the SSME powering the cargo carrier recommended in the ESAS report will be replaced with the RS-68.[2] RS-68 engines offer lower cost and higher thrust; however, they also are less efficient (on a thrust-per-weight basis) than the SSMEs. That limitation could require the use of a powered second stage on the cargo carrier. (The Longfellow also features RS-68 engines in the first stage but adds a liquid-fueled second stage to overcome that limitation.) CBO lacks a detailed description of the evolving design of the cargo carrier and, therefore, has not considered that recent development among its alternatives.

1. See, for instance, comments from NASA's manager of Constellation Systems Launch Vehicles Project at the Marshall Space Flight Center, cited by Frank Morring Jr. in "Tight Schedule; Crew Launch Vehicle Targets 2012 Human Mission; Challenges Abound," *Aviation Week & Space Technology*, April 24, 2006, p. 32.

2. Frank Morring Jr. in "Bigger Prop Tank Was Key to NASA's RS-68 Decision," *Aerospace Daily & Defense Report*, May 22, 2006.

APPENDIX

A

On-Orbit Assembly, Launch Vehicle Reliability, and Overall Probability of Mission Success

On-Orbit Assembly

Relying on multiple launches to execute a manned lunar mission requires the capability to assemble various hardware subcomponents into a functional whole in low earth orbit (LEO). Such assembly requires that the subcomponents be designed to rendezvous in space and dock with one another. Those operations can be accomplished by humans (either remotely from the ground or locally in LEO) or autonomously. In constructing the International Space Station (ISS), the National Aeronautics and Space Administration (NASA) has gained experience assembling a large mass in orbit using a crew on-site. (The space shuttle was used to lift into LEO subcomponents of the ISS that were later assembled by the shuttle's crew.) During all of the Apollo lunar missions, the command and service module and the lunar module performed undocking and redocking maneuvers while in flight. Those operations were controlled locally by the crew in the command and lunar modules.

The Russians have demonstrated the ability to rendezvous and dock in space using remote control. In particular, since 1989 their Progress program has flown the Progress M and the Progress M1 on 55 flights to the former Mir space station and to the ISS with only one failure. (In 1997, the Progress M collided with the MIR and damaged it, although not catastrophically.) Incapable of carrying a crew, the Progress vehicles delivered cargo to either the MIR or the ISS.

The United States has not successfully demonstrated rendezvous and docking by remote control or autonomously. NASA launched a Demonstration of Autonomous Rendezvous Technology (DART) spacecraft in April 2005 to rendezvous with and conduct close-proximity maneuvering about a target spacecraft. However, the mission terminated early, and NASA reported that the DART spacecraft had experienced, among other problems, irregularities in its navigation system.[1] The Department of Defense is pursuing initiatives similar to DART. One is the Orbital Express program, which is designed to demonstrate on-orbit satellite servicing; it is scheduled for launch in late 2006. Another is the XSS-11 mission, which successfully rendezvoused with its launch vehicle in April 2005 and is scheduled to spend a year rendezvousing (but not docking) with other objects in orbit.

With no directly relevant experience, it is difficult to assign a probability of success to eventual assembly operations that might be conducted by the United States—either remotely or autonomously—in an effort to return humans to the moon. Using the demonstrated success of the Russian Progress program—0.982—as a benchmark, CBO performed a parametric analysis of the likelihood of a manned lunar mission's failing using probabilities of success for on-orbit assembly that ranged from 0.98 to 0.99. In that analysis, the crew-assisted docking that would follow the launch of the crew carrier spacecraft is assumed to be successful.

Launch Reliability

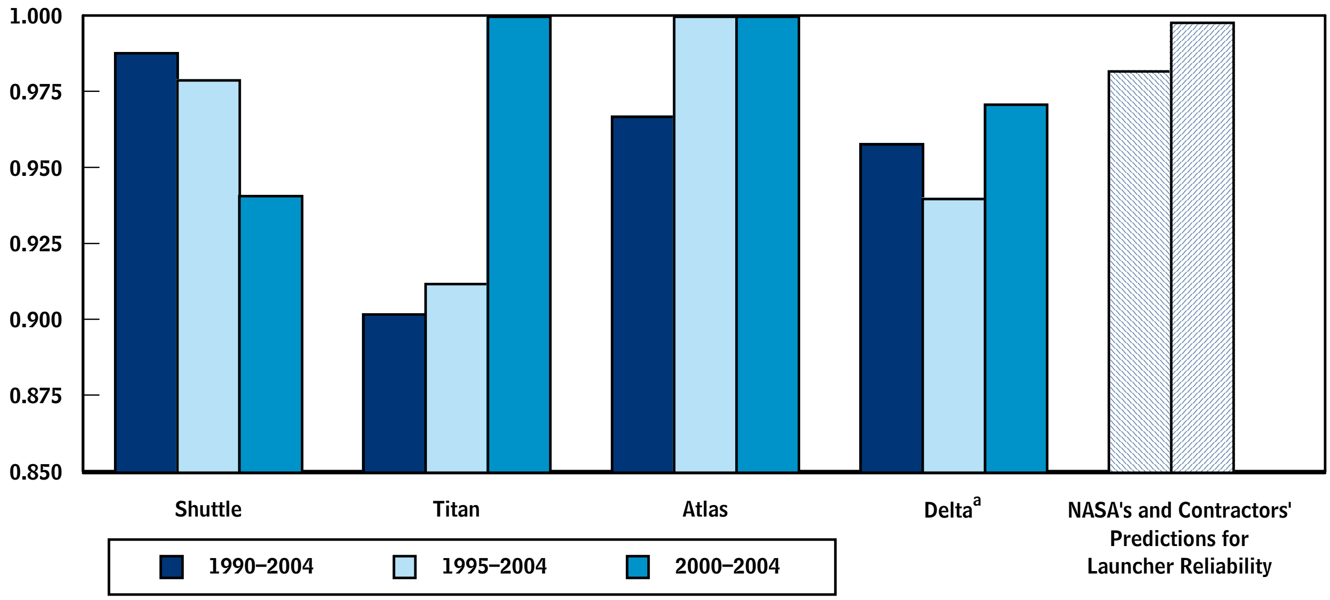
CBO's parametric analysis uses probabilities of successful launch ranging from 0.959 to 0.998. The lower bound of that range is the 15-year average of successful launches of the Atlas, Delta, and Titan expendable launchers, as well

1. NASA, *Overview of the DART Mishap Investigation Results*, available at www.nasa.gov/pdf/148072main_DART_mishap_overview.pdf.

Figure A-1.

Historical Launch Reliability

(Probability of successful launch)



Source: Congressional Budget Office.

a. The Delta IV heavy-lift launcher, included in these averages, accomplished test objectives but failed to place its dummy payload into the intended orbit.

as the space shuttle (see Figure A-1). The upper bound is the average of the probabilities of successful launches projected by Boeing, Lockheed Martin, NASA, and ATK Thiokol for the launch vehicle options that each organization considered during 2005 prior to completion of NASA's Exploration Systems Architecture Study.

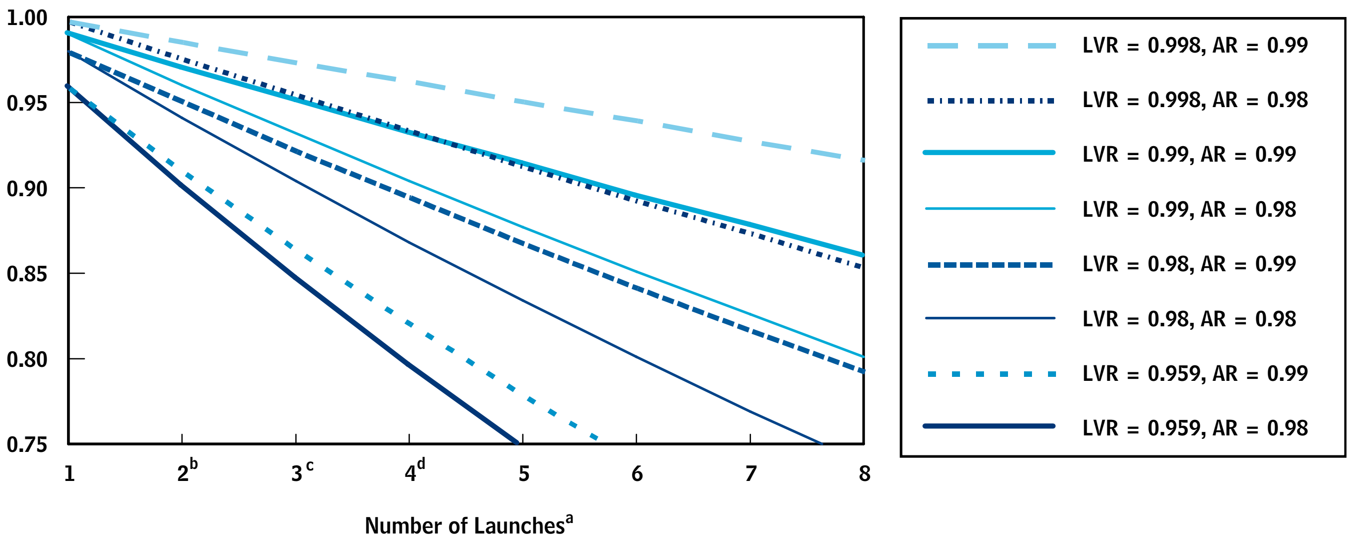
Overall Probability of Launch and Assembly Success

Not surprisingly, alternatives that require the least number of launches are least likely to experience a failure (see Figure A-2). The use of close-derivative launchers to execute a manned lunar mission would require three or four launches, with a probability of failure ranging from 3 percent to 21 percent. The use of the super-heavy alternatives, which would require two launches, would have a probability of failure of 2 percent to 10 percent.

Figure A-2.

Overall Probability of Mission Success

(Probability of successful launch and assembly)



Source: Congressional Budget Office.

Notes: AR = assembly reliability; LVR = launch vehicle reliability.

From 1990 to 2004, the average overall LVR of the shuttle and the Atlas and Delta families is 0.959.

a. The number of launches is N-1 cargo launches plus 1 crew launch. Reliability for docking the crew exploration vehicle with its cargo is assumed to be 1.0.

b. Probability of mission success with the super-heavy launchers.

c. Probability of mission success with the shuttle-derived Side-Mount, Longfellow, or Atlas V Heavy Plus cargo vehicles.

d. Probability of mission success with the Delta IV Heavy Plus cargo vehicle.

APPENDIX

B

Human Safety on Launch Abort

Human safety on launch abort is a primary consideration when distinguishing between the lift capacity of crew carriers and cargo carriers. As mentioned in Chapter 1, maximizing crew safety while maximizing launch vehicle lift capacity can be conflicting goals. No crew carrier considered in this Congressional Budget Office (CBO) report would fail to meet safety standards set by the National Aeronautics and Space Administration (NASA). However, trade-offs in design must occur to ensure crew safety, and those trade-offs affect the alternatives differently. Human safety during launch abort becomes an issue only if a mission has to be terminated because the launch has already failed to the degree that the crew must return to Earth safely before it reaches orbit.

Launch Trajectories and Launch Abort

The potential for death or injury during an aborted launch depends on the deceleration that the crew experiences as the spacecraft returns to Earth; that deceleration, in turn, depends on the launcher's trajectory on ascent. A launch vehicle that lifts its payload to a high altitude quickly is said to fly a steep trajectory; a launcher that ascends to a high altitude more gradually is said to fly a shallow or depressed trajectory. In general, the more depressed the trajectory that a booster flies, the more work it has to do to lift its payload into orbit. Therefore, a given launcher will be able to deliver less payload to orbit if it flies a more depressed trajectory. However, more depressed trajectories are safer for crewmembers, if they must abort, because they fall less steeply back into the atmosphere. Hence, trajectories that tend to maximize payload delivery tend to reduce crew safety.

Both the magnitude of the deceleration that the crew experiences—measured in multiples of the acceleration of gravity at the Earth's surface, or g's—and the duration of the acceleration are relevant in determining whether a return trajectory might harm or kill the crew of a spacecraft. On the basis of data collected by the Air Force during tests of aircraft ejection seats, NASA has developed a standard for acceleration and its duration along the "eyeballs in" direction that should not be equaled or exceeded during a launch abort in order to ensure the survival of the spacecraft's crew (see Figure B-1).[1]

A Comparison of the Alternatives

To be deemed safe, a launch vehicle must fly an ascent trajectory that, in the case of launch abort, would result in a return trajectory that satisfied NASA's safety standard. (As illustrated in Figure B-1, the vehicle would fly trajectories with curves of acceleration versus duration that lie below the curve labeled "NASA Standard.") Because the existing evolved expendable launch vehicles (EELV) lift their unmanned cargo payloads along relatively steep trajectories, the EELV-derived crew carriers considered by CBO generally reduce payload capability and adopt depressed trajectories to maintain a safe profile for manned flight. The space shuttle's abort trajectory has substantial margin in meeting NASA's safety standard, as would the five-segment, shuttle-derived crew carrier.

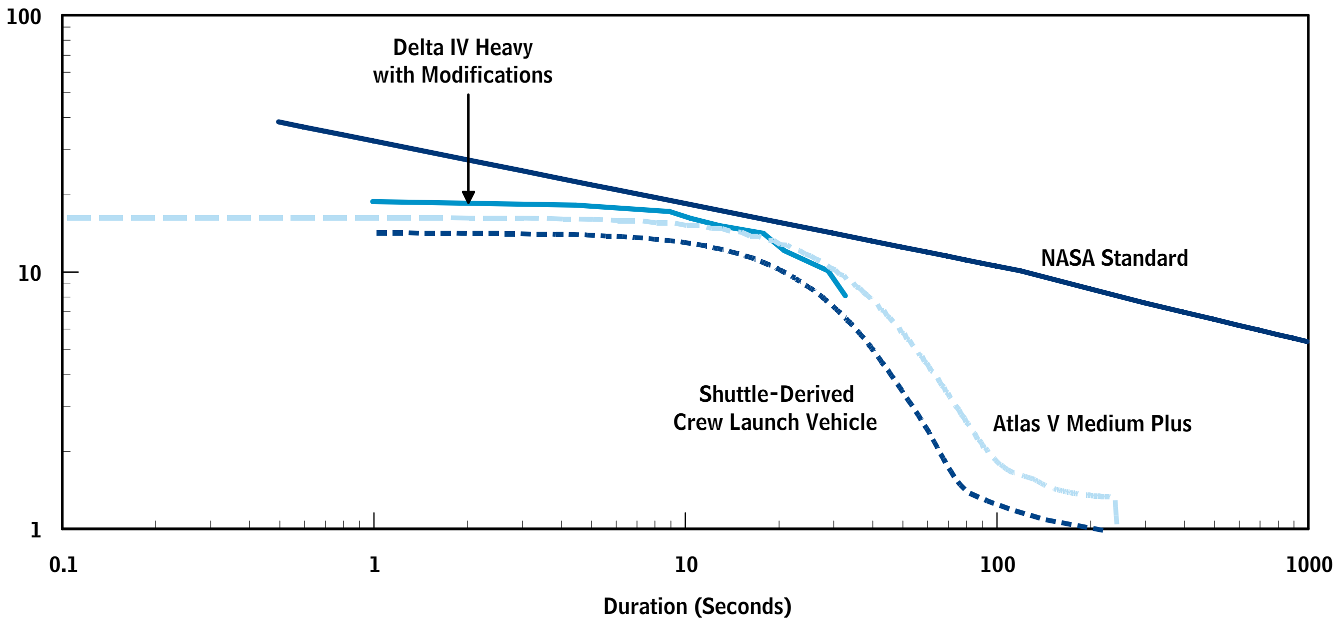
Analogous calculations for the Saturn V launcher were performed for CBO by the staff of ATK Thiokol. Those calculations indicate that if a launch abort had occurred during the Apollo program, the Saturn V launcher's trajectory on ascent could have subjected the Apollo command module's crew to unsafe decelerations during its return to Earth (see Figure B-2).

1. The "eyeballs in" direction assumes that the crewmembers reenter the atmosphere oriented so that their backs face the direction of motion. Other orientations also are important, but the eyeballs in direction is used here to make comparisons.

Figure B-1.

Acceleration on Launch Abort for Various Launch Vehicles

(Acceleration, or g's, in the $+G_x$ "eyeballs in" direction)



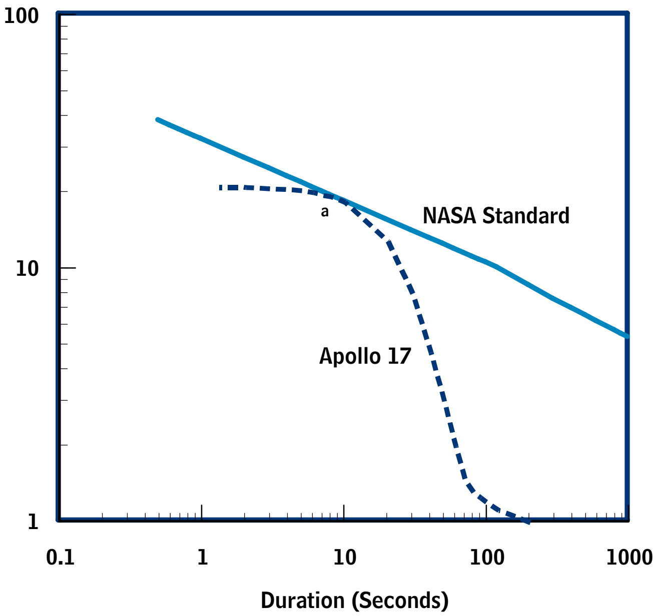
Sources: Congressional Budget Office based on contractors' estimates for launch vehicles. The NASA standard is from National Aeronautics and Space Administration, *Man-Systems Integration Standards,* NASA-STD-3000, vol. 8, *Crew Exploration Vehicle Launch Segment* (2005).

Note: Force is expressed in multiples of terrestrial surface gravity (g's). The direction of force is eyeballs in (with deceleration pressing on the astronauts' chests and eyes as they lie on their backs while descending toward Earth).

Figure B-2.

Acceleration on Launch Abort for Apollo 17

(Acceleration, or g's, in the $+G_x$ "eyeballs in" direction)



Sources: The NASA standard is from National Aeronautics and Space Administration, *Man-Systems Integration Standards,* NASA-STD-3000, vol. 8, *Crew Exploration Vehicle Launch Segment* (2005). The Apollo 17 calculations were done for the Congressional Budget Office by ATK Thiokol.

Note: Force is expressed in multiples of terrestrial surface gravity (g's). The direction of force is eyeballs in (with deceleration pressing on the astronauts' chests and eyes as they lie on their backs while descending toward Earth).

a. Apollo 17's maximum abort acceleration slightly exceeds the NASA standard.

APPENDIX

C

Considerations That Affect Lunar Missions Executed Using Multiple Launches

A lunar mission that relied on multiple launches into low earth orbit (LEO) would be subject to constraints that would not affect missions conducted with a single Apollo-style launch. A primary constraint is the need to ensure that all the launches were executed in a short enough span of time to preclude substantial leakage of the cryogenic hydrogen fuel stored in orbit, which would be used to launch the assembled spacecraft from LEO to the moon. That constraint would make it necessary to account for potential launch delays and manage actual delays caused by problems related to weather, range safety issues, and launch vehicle performance. The potential need to launch other spacecraft from the same launch pad(s) used for launching manned lunar missions could cause scheduling constraints, which also must be considered.

Hydrogen Leaks

Hydrogen molecules are the lightest in existence and, therefore, are quite volatile. Consequently, anything containing hydrogen, even in the cold, near-vacuum conditions of space, leaks readily.[1] Assuming a predetermined mission length and launch schedule, launch vehicle designers plan for the excess hydrogen fuel needed to compensate for the leakage. (For example, about 34 percent of the mass of hydrogen fuel stored in LEO might leak from its on-orbit storage container during one year.)[2] However, once a payload is placed into LEO with a given amount of cryogenic hydrogen fuel on board, other launches must proceed according to the assumed schedule or too much hydrogen will boil away, leaving insufficient amounts of fuel to propel the assembled lunar mission out of LEO and to the moon.

Launch Cycle

A launch cycle generally consists of two phases: the time that is required at a launch complex to assemble and ready the launch vehicle and payload involved in a single launch, and the time required to both execute the launch and refurbish the complex for the next anticipated launch. Infrastructure at the shuttle launch complex and at the launch complex that serves the Atlas evolved expendable launch vehicle (EELV) can support one launch every 30 days. The launch cycle for the Delta EELV launch complex is 21 days. Therefore, as currently configured and if fully staffed, the shuttle and Atlas complexes could each support 12 launches annually, and the Delta complex, 18.

Launch Delays

Most delays, or at least their duration, can be anticipated and accommodated within the launch cycle. Approximately one-third of Air Force launches occur on time. Another third of launches occur with a delay that can be accommodated within the launch cycle. And roughly one-third of launches are delayed until later launch cycles.[3] About 50 percent of those launch delays are

1. Oxygen and other gases also leak but not as extensively, which is why hydrogen leakage usually dominates considerations.

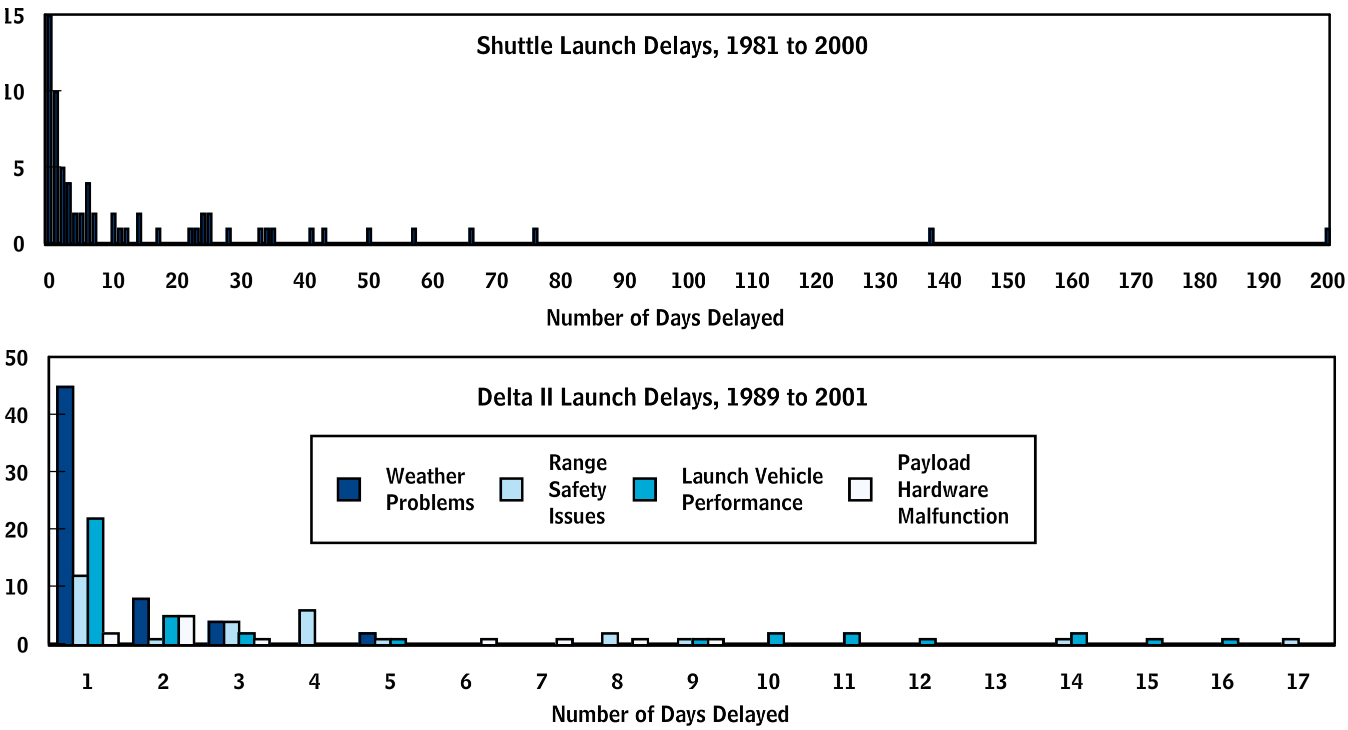
2. Actual boil-off rates are complex functions of the material used to construct the storage container, its geometry, and whether and how passive and/or active cooling techniques are employed. A boil-off rate of 34 percent is typical for passive cooling techniques and traditional storage containers.

3. Data extracted from the U.S. Air Force's Eastern Range Launch Performance, 1988 to 2002.

Figure C-1.

Historical Launch-Pad Delays for Selected Launch Systems

(Number of launches)



Source: Congressional Budget Office based on data from shuttle-mission-delay records and from D.P. Thunnisen, *Balancing Cost, Risk, and Performance Under Uncertainty in Preliminary Mission Design* (Reston, Va.: American Institute of Aeronautics and Astronautics, 2004).

caused by weather, 42 percent are caused by malfunctioning hardware (in the launch vehicle, payload, or sensing systems prior to launch), and 8 percent are caused by range problems (such as the failure of a tracking camera or other sensor used to monitor the launch downrange after the vehicle's launch or prior to its reaching orbit).

The typical delay is usually of short duration. Simpler launchers like the Delta II have experienced an average launch delay of only 2.4 days, whereas more complex launch systems can suffer longer delays (see Figure C-1). The shuttle's average delay has been 12 days.

To accommodate such delays, launch cycle missions contain built-in margins. For instance, for the Atlas EELV, a four-day margin is built into the schedule. In addition, a typical launch cycle will assume that work is conducted five days per week, with no work performed on weekends. Therefore, a 30-day launch cycle may have a built-in allowance for delays of up to about 12 days.

Experience indicates, however, that some very long launch delays can occur, particularly for the more complex launchers (see Figure C-1). A less complex launcher like the Delta II experiences launch delays that exceed 12 days about 4 percent of the time. The more complex space shuttle has experienced launch delays that last longer than 12 days about 20 percent of the time, but it also has experienced delays of longer than 30 days about 10 percent of the time.

Launch Delays and Launch Cycles

Because there is some chance that complex launch vehicles will experience a long delay, the total number of launch cycles available to lift the components of a manned lunar mission can become a key consideration.

Table C-1.

Launch Cycles Needed to Ensure Mission Success

T	L	D	L + D
		p = 0.9	
0.99	4	3	7
0.99	2	2	4
0.999	4	4	8
0.999	2	3	5
		p = 0.85	
0.99	4	4	8
0.99	2	3	5
0.999	4	5	9
0.999	2	4	6

Source: Congressional Budget Office based on data provided by Boeing, Lockheed Martin, and ATK Thiokol.

Note: T = threshold of success (percent); L = required launches per mission; D = number of additional launch cycles planned for delays; L + D = number of launch cycles necessary for mission success to exceed T; p = probability of launch within a given launch cycle, which is assumed to be equal for all launches associated with a given mission.

This is particularly true if the number of mission launches is large. In general, the number of launch cycles available for existing launchers would be sufficient to accommodate both manned lunar missions and other launches, providing the former occurred without appreciable delay. However, if delays became too long, then current launch capacity could be insufficient. The following calculation indicates the interplay between launch cycle capacity and launch delay.

Let:

L = the number of launches required for a manned lunar mission (L ranges between 2 and 4 for the alternative launchers considered by the Congressional Budget Office);

B = the boil-off constraint in launch cycles (B is the number of launch cycles within which hydrogen boil-off is not a constraint. For instance, if the launch cycle is one month, and boil-off becomes a problem after eight months, then $B = 8$);

D = the number of additional launch cycles put into a mission's launch schedule to accommodate the possibility of delays;

p = the probability that a given launch will occur within one launch cycle (for example, the data for the shuttle and Delta II suggest that launches of manned lunar missions might occur within the planned launch cycle about 90 percent of the time, or $p = 0.9$); and

T = the desired probability that all launches occur on schedule (for instance, $T = 0.99$ would reflect the desire that all L launches occur within $L + D$ launch cycles at least 99 percent of the time).

Using that framework, the minimum number of added launch cycles, D, that must be built into a launch schedule to ensure the desired probability, T, of executing all launches on schedule can be computed as a function of the number of launches needed, L, and the probability that a single launch occurs within one launch cycle, p.

In equation form, the relationship between these variables can be expressed by the inequality:

$$T \leq p^{L} \sum_{i=0}^{D} (1-p)^{i} \binom{L+i-1}{i}$$

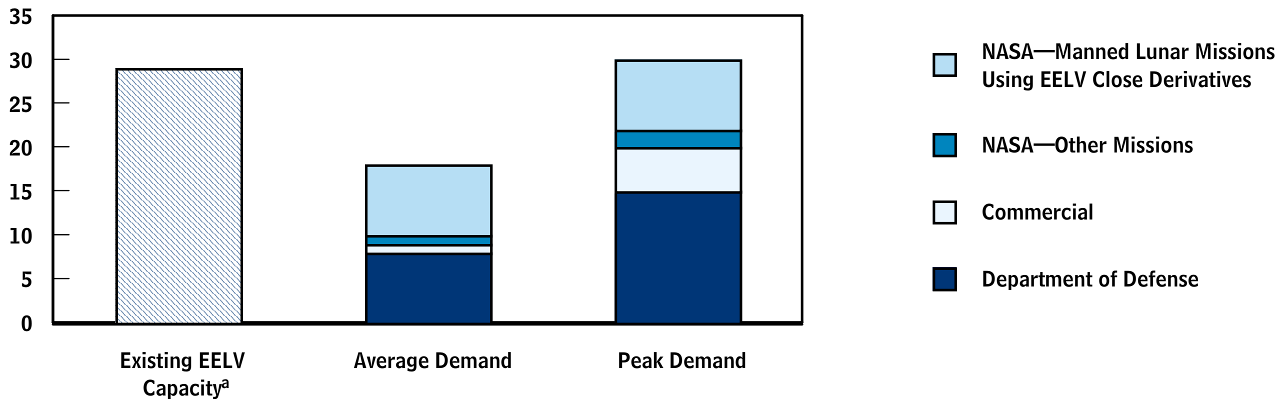
If it is desired that T be 0.99 or greater, the total number of launch cycles that must be incorporated ($L + D$) in constructing a launch schedule for a manned lunar mission would be about twice, or more, the number of launches needed (L). (See Table C-1.)

There are two additional constraints on D. One expresses the requirement that $L + D$ not exceed B, or $L + D <= B$. The results displayed in Table C-1 indicate that planning to launch enough hydrogen fuel to accommodate six months of leakage ($B = 6$) might be an insufficient margin if the close-derivative launchers ($L = 3$ or 4) considered by CBO were used to execute a manned lunar mission from the same launch pad. That margin would probably be sufficient, however, if most of the super-

Figure C-2.

EELV Annual Launch Capacity and Potential Demand

(Number of launch cycles)



Source: Congressional Budget Office.

Notes: EELV = evolved expendable launch vehicle; NASA = National Aeronautics and Space Administration.

The "Average Demand" column displays the arithmetic average of the demand projected for the period spanning 2005 through 2020 for Department of Defense and commercial launches; the arithmetic average of the demand projected by NASA for launches of other than manned lunar missions for the period spanning 2005 to 2012; and CBO's estimate of the launches needed to execute manned lunar missions through 2020 using the pure Delta-derived alternative. The term "pure" means that both the crew carrier and the cargo carrier are derived from vehicles in the same family of launchers.

The "Peak Demand" column displays the maximum annual demand projected for each mission over the time periods considered.

a. A potential surge capacity of up to about 35 launch cycles is possible.

heavy launchers considered by CBO were used (L = 2, which excludes the Longfellow).

A second constraint on D is that consecutive launch cycles not conflict with other launch demand. For all super-heavy alternatives and the shuttle-derived close derivatives, the launch pads and other facilities used would be dedicated exclusively to launching lunar missions; therefore, conflict would not be an issue. For the EELV close-derivative launchers considered by CBO, however, conflict would be an issue because those launchers would use the same launch pads and facilities now used for launching Atlas and Delta EELVs. In particular, during years in which demand peaks for EELV launches that support other than manned lunar missions, existing capacity would be barely sufficient to accommodate the demand for those launches as well as the EELV launches needed to conduct manned lunar missions (see Figure C-2). In case a single launch vehicle proved unreliable, that near sufficiency could put the Air Force's desire for assured access at risk.[4]

4. The Air Force's policy of assured access is a justification for both the Atlas V and Delta IV lines of launchers. In the absence of Vision for Space Exploration missions, either one of those lines has the infrastructure in place to meet (or, in 2012, to nearly meet) the Air Force's launch demands to place payloads of up to about 20 metric tons in orbit. Peak demands are taken from an Air Force manifest of projected launch demand through 2020. However, the recent flight history of the EELV program suggests that actual flights may be significantly lower than projections.

APPENDIX

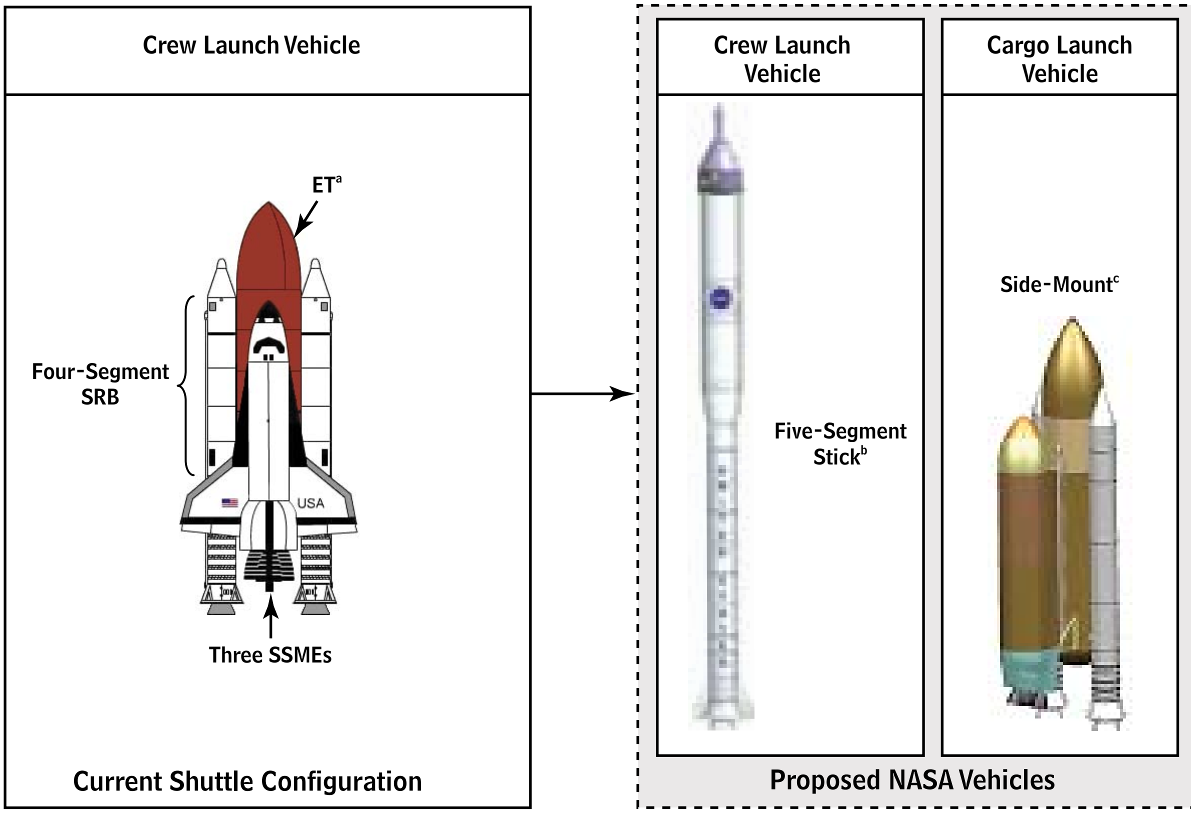
D

Schematic Depictions of Launch Vehicle Derivatives and Their Antecedents

The figures in this appendix—which, within a given figure, are drawn to scale—depict the crew and cargo launch vehicles considered by the Congressional Budget Office under various alternatives. Their antecedent launch systems are also included.

Figure D-1.

Proposed Modifications to Generate the Shuttle Close Derivatives



Source: Congressional Budget Office based on information provided by Boeing, Lockheed Martin, and ATK Thiokol.

Note: ET = external tank; SRB = solid rocket booster; SSMEs = space shuttle main engines.

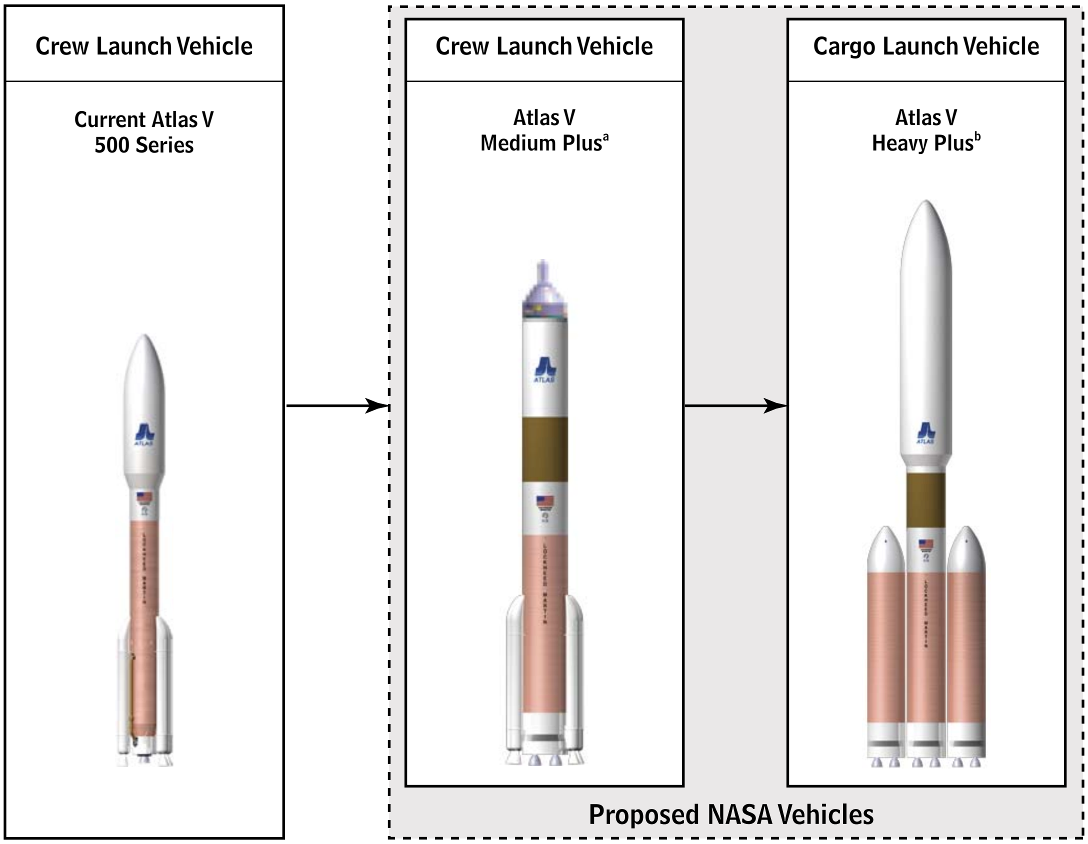
a. The main propulsion system for the shuttle is composed of three "sticks": two four-segment SRBs attached to the ET (the third stick).

b. Modifications would include increasing the four-segment SRBs to five segments each, adding a new upper stage using a simplified version of the J-2 engine (J-2S) from Saturn V, and adding a new launch vehicle human monitoring system.

c. Modifications would include using the existing SRBs and ET, and developing a new, expendable payload carrier with three simplified SSMEs.

Figure D-2.

Proposed Modifications to Generate the Atlas V Close Derivatives



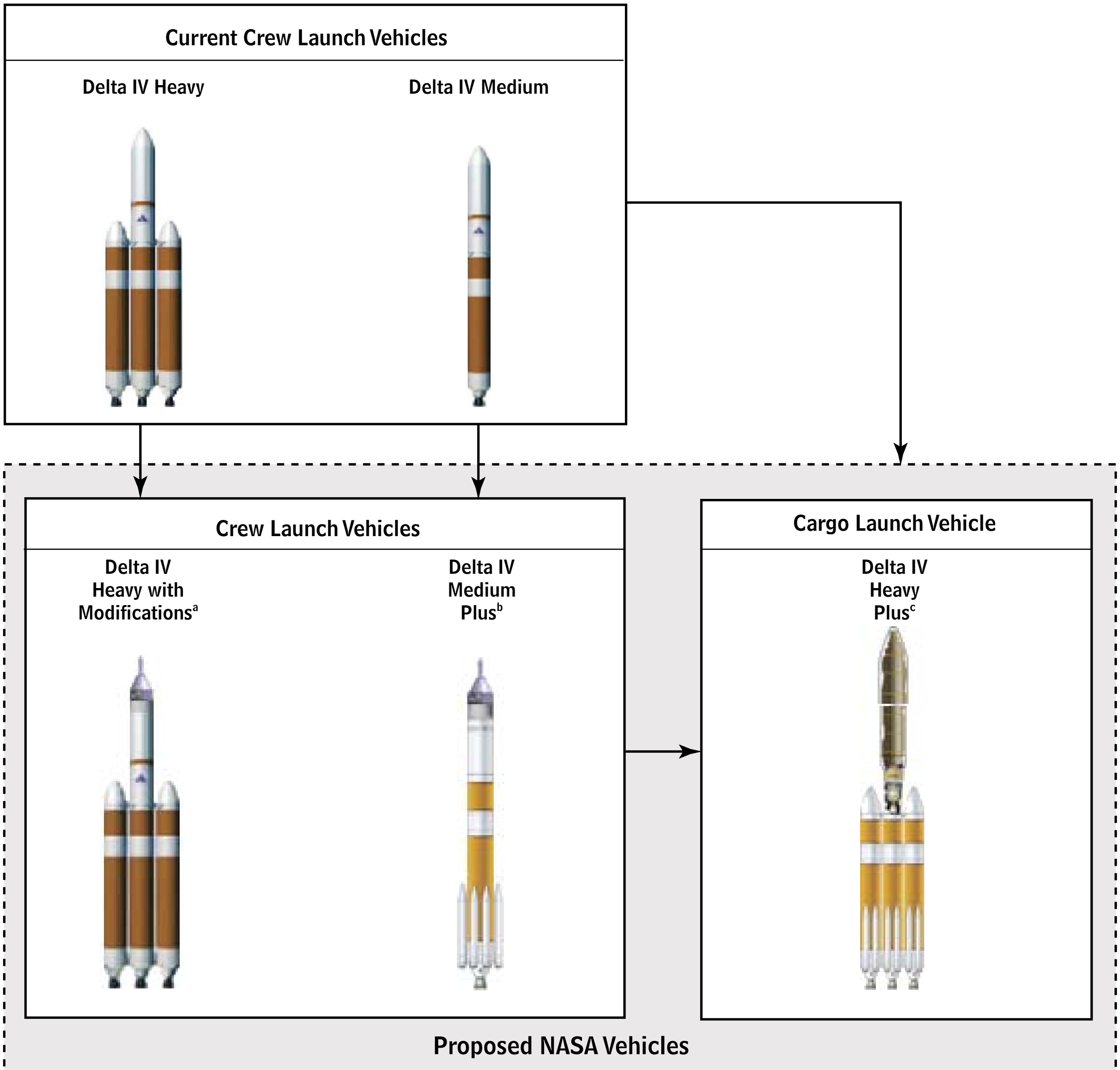
Source: Congressional Budget Office based on information provided by Lockheed Martin.

a. Modifications would include a new 5.4-meter first-stage booster tank and an upper-stage tank, two RD-180 engines for a booster, and four RL-10 engines for the upper stage. Reliability enhancements and a new launch vehicle human monitoring system would be added.

b. The Atlas V Heavy Plus would consist of a three-body version of the Atlas V Medium Plus, the same booster design, and the same upper-stage design. An expanded cargo shroud would be included.

Figure D-3.

Proposed Modifications to Generate the Delta IV Close Derivatives



Source: Congressional Budget Office based on information provided by Boeing.

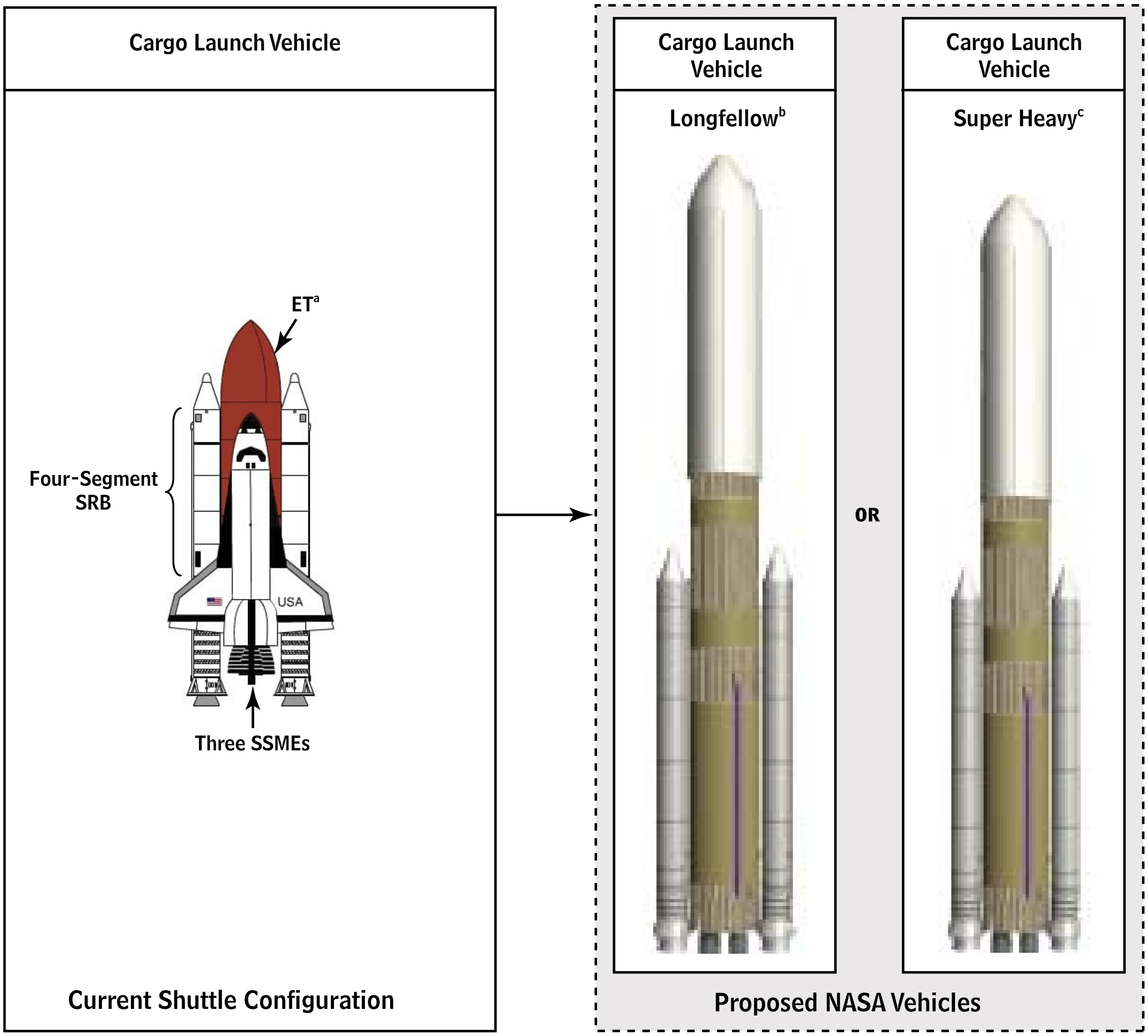
a. Modifications would include increased redundancy and new launch vehicle human monitoring systems, but the same cores and second stage would be used.

b. Modifications would include increased redundancy, new launch vehicle human monitoring systems, an enhanced first stage and six graphite epoxy motors (GEMs), and an enhanced second stage with three RL-10 engines.

c. The Delta IV Heavy Plus would include six GEMs, the same upper stage as the Delta IV Medium Plus, and a larger payload shroud.

Figure D-4.

Proposed Modifications to Generate the Shuttle-Derived Super-Heavy Launchers



Source: Congressional Budget Office based on information provided by NASA and Boeing, Lockheed Martin, and ATK Thiokol.

Note: EDS = earth departure stage; ET = external tank; SRB = solid rocket booster; and SSMEs = space shuttle main engines.

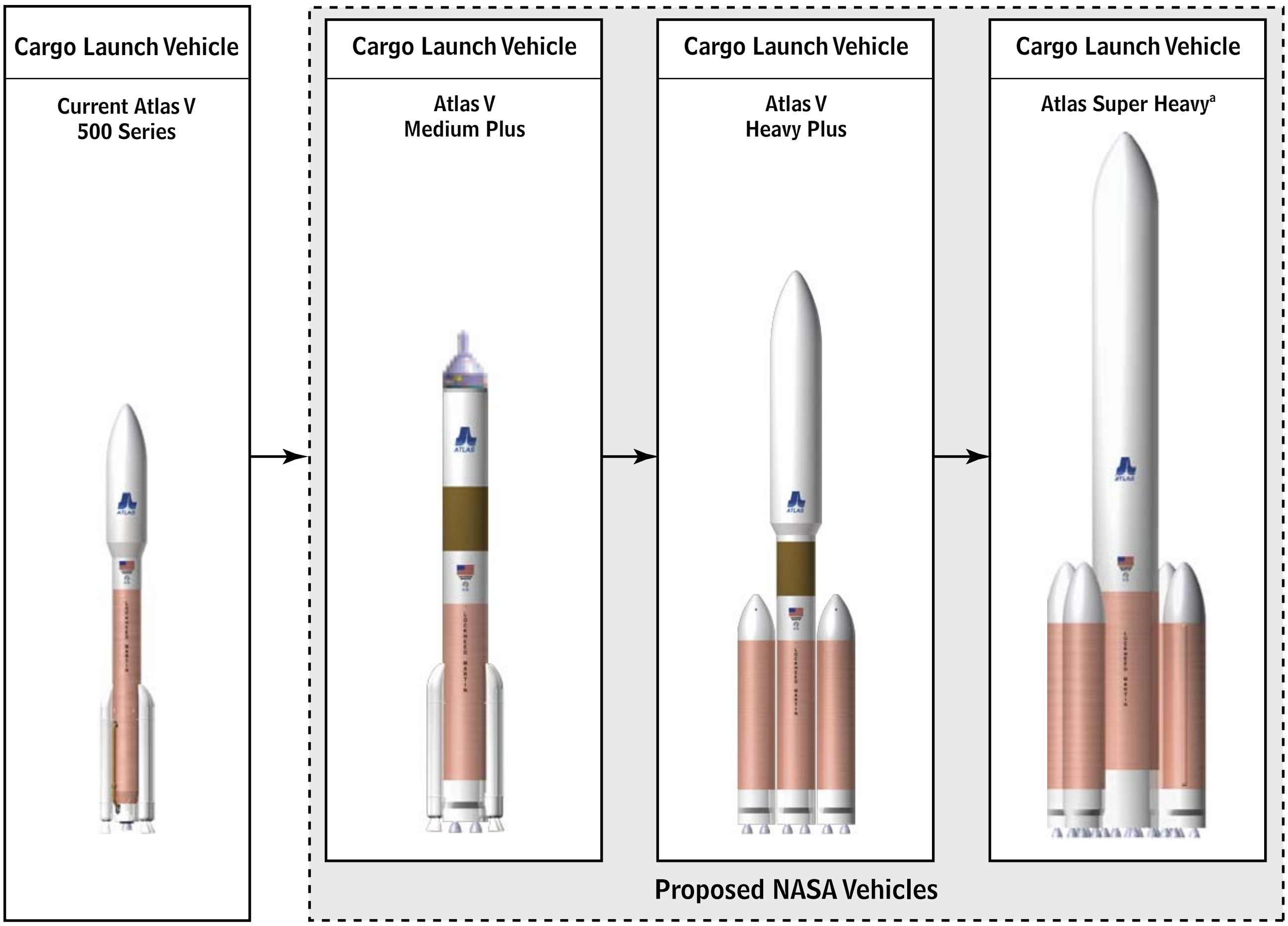
a. The main propulsion system for the shuttle is composed of three "sticks": two four-segment SRBs attached to the ET (the third stick).

b. Modifications would include using five-segment SRBs, developing a new first stage from a modified and stretched ET, and four RS-68 engines. A new second stage using one J-2S engine would be developed along with a new expendable payload carrier mounted above the new second stage. With its second stage, the Longfellow is about 393 feet high and about 15 feet taller than the super heavy.

c. Modifications would include using five-segment SRBs, developing a new first stage from a modified and stretched ET, and five SSMEs. The rocket would have no second stage (circular orbit requires a first burn of the EDS). A new expendable payload carrier mounted above a modified ET would also be developed.

Figure D-5.

Proposed Modifications to Generate the Atlas Super-Heavy Launcher

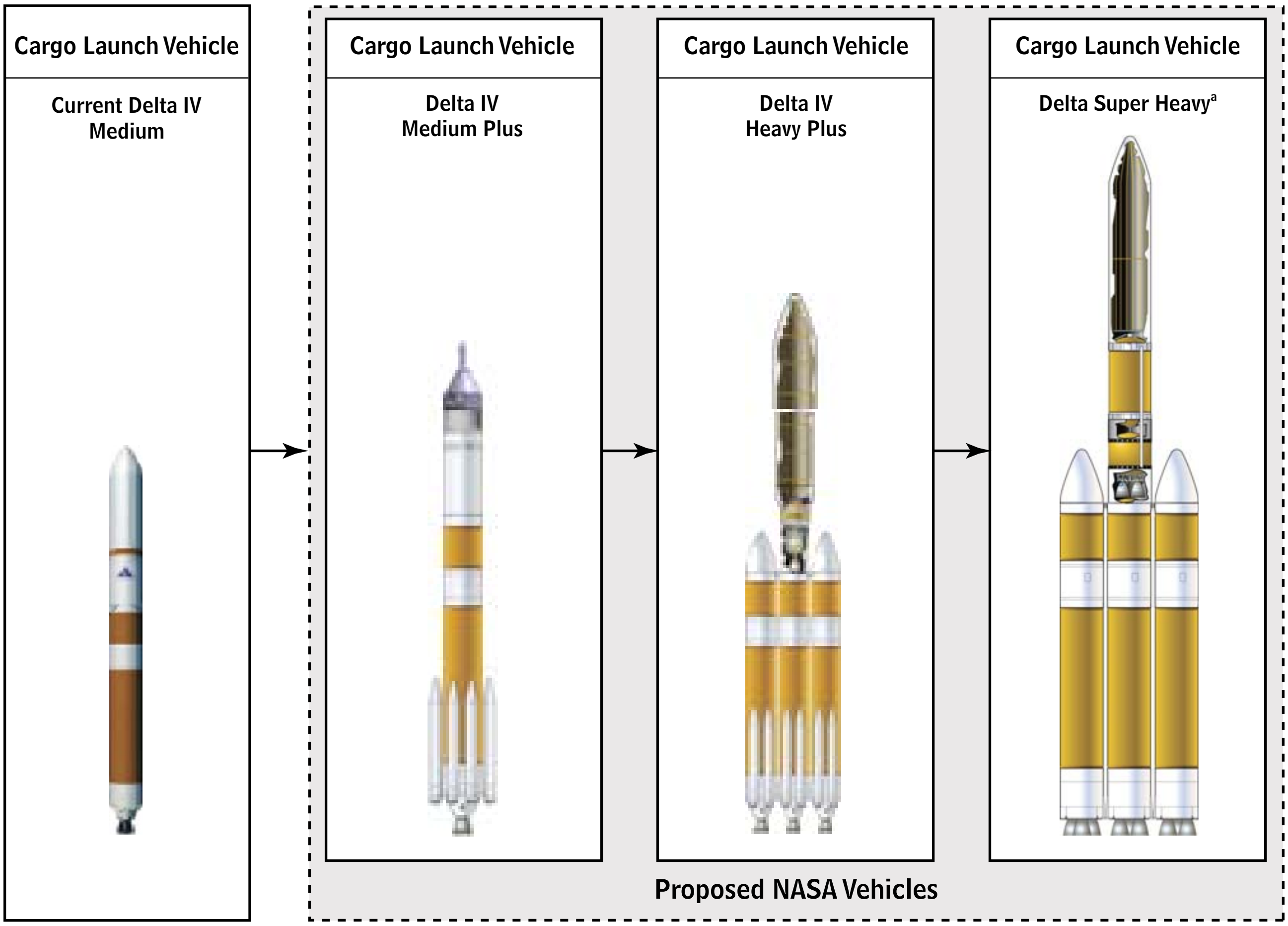


Source: Congressional Budget Office based on information provided by Lockheed Martin.

a. Modifications to the first stage would include a new 8.4-meter central core with five RD-180 engines and four liquid rocket boosters (LRBs) that are similar to the Atlas V Heavy Plus's LRBs. The second stage would include a Centaur second stage that is typical of the Atlas V Heavy Plus. A lengthened payload shroud would be added.

Figure D-6.

Proposed Modifications to Generate the Delta Super-Heavy Launcher



Source: Congressional Budget Office based on information provided by Boeing.

a. Modifications to the first stage would include three new 8-meter cores, each with four RS-68 engines. The second stage would consist of a new 8-meter stage with space shuttle main engines and a new, expanded 8-meter cargo shroud.

APPENDIX

E

Cost Estimates for Alternative Launch Systems

In this study, the Congressional Budget Office (CBO) examined two time frames that would enable the National Aeronautics and Space Administration (NASA) to meet future space-launch needs designed to further both human exploration of the solar system and a return to the moon. Each schedule takes into account a Presidential directive issued in January 2004 that called for a return mission to the moon no later than 2020. Subsequent to that directive, NASA concluded that a lunar mission in 2018 was feasible and announced plans to launch two lunar missions a year from that point forward. In addition, NASA has stated publicly that the new launch system used for lunar missions would also be used to service the International Space Station (ISS). On the basis of information provided by NASA, CBO estimates that between 15 and 25 ISS support missions would be launched.

The first path considered by CBO would achieve the more ambitious goal of two lunar missions a year by 2018 and would provide 25 ISS missions over the 2012-2016 period. The second path assumes that the moon missions would not start until 2020 and that the number of ISS missions, starting in 2014, would total only 15. For both paths, CBO considered six program alternatives that would meet the specific mission goals. Each alternative would involve purchasing two types of launch vehicles—one for transporting the crew and supporting the ISS, and a second, larger vehicle (called the cargo carrier) for lifting the rest of the lunar payload into orbit.

This appendix details the basis for the cost estimates developed for each of the six program alternatives, assuming they would be implemented under the more ambitious schedule. (Tables, however, may include data for both schedules.) Under the more ambitious schedule, each alternative would call for the purchase of 29 crew launchers and from four to 12 cargo launchers, depending on the lift capability of each cargo launcher. Some of the cargo launchers represent new, larger systems that would be able to lift payloads weighing in excess of 100 metric tons (mt). As a result, fewer of them would be required. Others are closer derivatives of existing systems that on a single launch lift between 40 and 77 mt into orbit. A description of the configuration and costs of the existing launchers is provided for clarity and because those existing systems form the basis for the estimates of the larger launch systems.

CBO calculates that costs to execute the more ambitious schedule for each of the six alternatives would range from $26 billion to $38 billion. Those estimates include nonrecurring and recurring costs incurred over the 2006-2017period. Nonrecurring costs include costs for modifying existing launch systems, designing and developing new launchers, and constructing or modifying launch pads for new launchers. Recurring costs include costs for purchasing launchers and launch services. All costs in this appendix are expressed in constant 2006 dollars.

Existing Launch Systems

Delta IV and Atlas V Launchers

The Delta IV is a two-stage launch vehicle built by the Boeing Corporation. Boeing produces five configurations of the launcher to place a mix of medium or heavy payloads into space. The first stage uses a booster core powered by an RS-68 engine, and the second stage is powered by an RL-10 engine. Both engines burn liquid hydrogen and liquid oxygen to generate thrust. The payload is encapsulated in a fairing for protection. The four Delta IV configurations that launch payloads weighing up to 13 mt into space use a single booster core that can be augmented with up to four solid rocket motors and a second stage that measures 4 or 5 meters in diameter. Those configurations are referred to as medium-lift launch vehicles.

The configuration that launches payloads weighing up to 25 mt uses three of the booster cores strapped together to provide greater lift and a 5-meter second stage. That configuration is called a heavy-lift launch vehicle.

The Atlas V, built by Lockheed Martin, is also a two-stage launcher. Lockheed Martin currently produces several configurations of the launcher that can place a mix of payloads weighing up to 20.5 mt into space. Those configurations are called Atlas V Medium (A5M) launch vehicles. Another configuration, designed but not being built, would be able to place heavier payloads into space. The A5M's first stage uses a booster core powered by an RD-180 engine, and the second stage is powered by one or two RL-10 engines. The RD-180 engine burns liquid oxygen and kerosene propellants to generate thrust, and the payload is encapsulated in a fairing for protection. All of the A5M configurations use a single booster core that can be augmented with up to five solid rocket motors and a second stage that measures slightly more than 3 meters in diameter. The configuration capable of launching heavier payloads would use three boosters strapped together to provide greater lift.

According to CBO's estimates, the cost to buy a medium-lift launch vehicle (defined in this appendix as a launcher capable of lifting fewer than about 20 mt) would be about $200 million: roughly $100 million to purchase the launcher and another $100 million to pay for launch services. The cost to buy a heavy-lift launch vehicle (capable of lifting about 25 mt) would total roughly $350 million: about $200 million to purchase the launcher and another $150 million to pay for launch services. The estimate for the medium-lift launch vehicle includes the cost of four solid rocket motors that would be strapped to the first-stage booster core. (For a breakdown of the estimates by cost category for each of the existing launchers, as well as estimates of the recurring costs for new launchers, see Table E-1.)

Information provided by the Air Force in budget justification materials to the Congress served as the basis for CBO's estimates. The Air Force calculates that the cost to buy 137 launch vehicles—125 medium and 12 heavy launchers—would total nearly $23 billion in 1995 dollars. After inflating that figure to 2006 dollars, CBO projects that the Air Force's estimate would increase to $28 billion. The Air Force has indicated that its estimated costs are almost evenly split between launchers and launch services, with about $15 billion paying for the launchers and $13 billion paying for launch services. Although the Air Force budget justification materials did not distinguish between the heavy launcher and medium launcher when considering costs, CBO was able to calculate separate estimates by assuming that each heavy launcher would cost about twice as much as a medium one. The factor of two assumes that the recurring cost for the booster core is about the same as the cost for the second stage. Therefore, a heavy launcher consisting of three booster cores and one second stage (four components) would cost twice as much as a medium launcher consisting of one booster core and one second stage (two components).

Similarly, CBO calculated the costs of placing a heavy launcher and a medium launcher into space. Based on information provided by the Air Force and Boeing, CBO developed a cost-estimating relationship that uses the weight of the launcher to determine costs for launch services. CBO concluded that launch service costs increase with launcher weight. Using that relationship, CBO estimates that the cost to place a heavy launcher (with a dry weight of about 85 mt) into space would be about 50 percent more than the cost of placing a medium launcher (weighing about 50 mt).

Space Shuttle

The space shuttle is made up of three main components—an orbiter, two solid rocket boosters (SRBs), and an external tank (ET). The orbiter serves as the crew's home in space and is powered by three space shuttle main engines (SSMEs) that burn liquid hydrogen and liquid oxygen to generate thrust. The cockpit is located in the forward fuselage, and the main engines are located in the aft fuselage. Mission payloads are carried in the mid-section of the orbiter. The two SRBs are each powered by a solid rocket motor. The motors burn solid fuel mixed with oxygen and provide most of the thrust to launch the space shuttle. The external tank contains the propellants used by the three main engines on the orbiter.

On the basis of information that NASA provided to the Congress in 2002 in budget justification materials, the cost to launch a space shuttle is about $900 million, assuming a launch rate of five missions per year. Unit costs would be higher with lower launch rates. Some components of the space shuttle, namely the orbiter and the SRB canisters, are reusable, and NASA refurbishes them after each launch. Although less than the cost of

Table E-1.

Comparison of Unit Recurring Costs for Selected Launchers

(Millions of constant 2006 dollars)

Launcher	Hardware	Launch Services	NASA Overhead	Total
		Existing Launchers		
Delta IV Medium (D4M)	100	100	c	200
Atlas V Medium (A5M)	100	100	c	200
Delta IV Heavy (D4H)	200	150	c	350
Space Shuttle	b	b	b	900
		Possible NASA Crew Launchers		
Delta IV Medium Plus (D4M+)	150	150	100	400
Atlas V Medium Plus (A5M+)	150	150	100	400
Delta IV Heavy with Modifications (D4H with Mods)	200	150	100	450
Five-Segment Single Stick[a]	200	150	100	450
		Possible NASA Cargo Launchers		
Delta IV Heavy Plus (D4H+)	250	200	150	600
Atlas V Heavy Plus (A5H+)	250	200	150	600
Side-Mount	450	300	200	950
Longfellow	550	300	250	1,100
Delta Super Heavy	850	300	350	1,500
Atlas Super Heavy	600	300	300	1,200
Shuttle-Derived Super Heavy	700	300	300	1,300

Source: Congressional Budget Office.

Notes: NASA = National Aeronautics and Space Administration. The estimates of recurring costs assume a purchase rate of four or five units per year for existing launchers and new crew launchers and a rate of two a year for the new cargo launchers. The estimate of overhead costs for new launchers is calculated by multiplying the launcher and launch-service costs by 30 percent.

a. The main propulsion system for the shuttle is composed of three "sticks": two four-segment solid rocket boosters attached to the central external tank (the third stick).

b. Breakdowns of costs by category are not available.

c. These launchers do not incur NASA overhead costs because they are used by the Air Force to launch military payloads into space.

purchasing new components, the cost to refurbish the orbiter and SRBs is significant.

New Launch Systems

As noted earlier, this CBO study examined six alternatives for purchasing new launch systems to support missions both to the moon and to the ISS. Four alternatives would involve buying launchers that either are derivatives of or use components of the Delta IV and Atlas V launchers; two alternatives would call for purchasing launchers that either are derivatives of or use components of the space shuttle. (For a summary of costs for the six alternatives assuming the more ambitious schedule, see Table E-2.) The costs vary from $26 billion to $38 billion. All the alternatives call for the purchase of 29 crew launchers—25 for ISS missions and four for lunar missions. Appropriations for those purchases would start in 2010. Depending on the alternative, either four, eight, or 12 cargo launchers would be purchased, starting in 2016.

The technical characteristics and costs for launchers that would be purchased for each alternative are provided below. In many cases, CBO employed cost-estimating relationships developed jointly by NASA and the Air Force that use the weight of a launcher's components to estimate the cost of those components. (The cost-estimating relationships are contained in the NASA-Air Force Cost Model, or NAFCOM.)

Alternative 1

According to CBO's estimates, 29 crew launchers and 12 cargo launchers would be purchased under this alternative (see Table E-2). The cost to develop and purchase those launchers would total about $28 billion over the 2006-2017 period, CBO estimates.

CBO assumed that the crew launcher would be a variant of the Delta IV Medium launcher, known as the Delta IV Medium Plus (D4M+). The D4M+ would use the same first-stage booster core currently used by the Delta family of medium launchers with six solid-fuel rocket motors. The D4M+ would increase the length of the second stage on the medium launchers by about 20 percent, adding two RL-10 engines. Because the new launch system would be used as a crew launcher, state-of-the-art features would be incorporated to aid human flight. Also, more safety features would be added to conform with NASA's standards for a manned launch.[1]

Allowing for about $3.5 billion in nonrecurring costs and roughly $12 billion in recurring costs, CBO estimates that the crew launcher would cost about $15 billion over all. The estimate of nonrecurring costs includes the following:

- about $1.4 billion for redesigning the current medium launcher to the D4M+ configuration, on the basis of information provided by the Delta IV contractor;
- about $1.1 billion for three test flights, using the recurring per-unit cost estimates that are discussed later in this appendix but increasing those estimates by 30 percent (a factor of 1.3) consistent with NAFCOM methods for estimating the cost of test-flight assets;
- about $0.3 billion for modifying launch pads, based on information provided by the contractor on the nature of the needed modifications;
- about $0.8 billion for the costs of program management and systems engineering—overhead—associated with NASA launch activities, assuming a 30 percent burden rate.[2] (For all estimates, CBO assumes that costs would be increased by 30 percent to account for NASA's overhead.)

1. The safety and human aids collectively fall under NASA's launch vehicle health management (LVHM) system.

The estimate of recurring costs of about $12 billion includes the cost of buying 29 D4M+ launchers, at an average cost of about $400 million each. As shown in Table E-1, the estimate of per-unit recurring costs includes about $150 million in launch vehicle costs, $150 million in launch service costs, and $100 million in overhead.

CBO assumed that the cargo launcher would be a variant of the Delta IV Heavy launcher, known as the Delta IV Heavy Plus (D4H+). The D4H+ would use the same first-stage booster cores and second stage currently featured on the Delta IV Heavy launcher but would add two solid-fuel rocket motors to each of the three booster cores and add two RL-10 engines to the second stage. Those changes would allow the new launch system to be used as a cargo launcher with a payload lift of about 40 mt.

According to CBO's estimates, the cargo launcher would cost about $12 billion—about $5 billion in nonrecurring costs and about $7 billion in recurring costs (see Table E-2). The estimated nonrecurring costs include the following:

- about $1.1 billion for redesigning the current heavy-lift launcher to the D4H+ configuration, on the basis of information provided by the Delta IV contractor;
- nearly $1.6 billion for conducting three test flights;
- about $0.3 billion for modifying the launch pads, on the basis of information provided by the contractor on the nature of the needed modifications;
- about $1 billion for "mothballing" many NASA launch facilities (as a result of not using Pad 39, now used by the space shuttle), on the basis of information provided by NASA; and
- about $1.2 billion for NASA overhead.

The estimate of recurring costs includes the cost of buying 12 D4H+ launchers, at an average cost of about $600 million each (see Table E-1 for detailed information on the breakout of recurring costs).

2. The burden rate assumes full cost accounting and represents government overhead associated with the staffing and maintenance of NASA's facilities.

Table E-2.

Summary of Costs for Space Exploration Alternatives from 2006 to 2017

(Billions of constant 2006 dollars)

			Costs		
Alternative	Set of Launchers	Purchase Quantity	One-Time	Recurring	Total
		More Ambitious Schedule			
1	Crew: Delta IV Medium Plus (D4M+)	29	3.3	12.0	15.5
	Cargo: Delta IV Heavy Plus (D4H+)	12	5.2	7.2	12.4
	Total		**8.7**	**19.2**	**27.9**
2	Crew: Atlas V Medium Plus (A5M+)	29	5.3	12.0	17.4
	Cargo: Atlas V Heavy Plus (A5H+)	8	4.0	4.8	8.8
	Total		**9.3**	**16.8**	**26.1**
3	Crew: Five-Segment Stick[a]	29	4.8	13.5	18.3
	Cargo: Side-Mount	8	4.7	7.6	12.3
	Total		**9.5**	**21.1**	**30.6**
4	Crew: Delta IV Medium Plus (D4M+)	29	3.5	12.6	15.5
	Cargo: Delta Super Heavy	4	16.7	6.0	22.7
	Total		**20.2**	**18.0**	**38.2**
5	Crew: Atlas V Medium Plus (A5M+)	29	5.3	12.0	17.3
	Cargo: Atlas Super Heavy	4	9.0	4.8	13.8
	Total		**14.3**	**16.8**	**31.1**
6	Crew: Five-Segment Stick[a]	29	4.8	13.5	18.3
	Cargo: Shuttle-Derived Super Heavy	4	8.9	5.2	14.1
	Total		**13.7**	**18.7**	**32.4**
		Less Ambitious Schedule			
1	Crew: D4M+	15	3.5	6.0	9.5
	Cargo: D4H+	0	5.2	0.0	5.2
	Total		**8.7**	**6.0**	**14.7**
2	Crew: A5M+	15	5.3	6.0	11.3
	Cargo: A5H+	0	4.0	0.0	4.0
	Total		**9.3**	**6.0**	**15.3**
3	Crew: Five-Segment Stick	15	4.8	6.8	11.6
	Cargo: Side-Mount	0	4.7	0	4.7
	Total		**9.5**	**6.8**	**16.3**
4	Crew: D4M+	15	3.5	6.0	9.5
	Cargo: Delta Super Heavy	0	16.7	0.0	16.7
	Total		**20.2**	**6.0**	**26.2**
5	Crew: A5M+	15	5.3	6.0	11.3
	Cargo: Atlas Super Heavy	0	9.0	0.0	9.0
	Total		**14.3**	**6.0**	**20.3**
6	Crew: Five-Segment Stick	15	4.8	6.8	11.6
	Cargo: Shuttle-Derived Super Heavy	0	8.9	0.0	8.9
	Total		**13.7**	**6.8**	**20.5**

Source: Congressional Budget Office.

Note: The more ambitious schedule would involve purchasing 25 crew launchers to support the International Space Station (ISS) starting in 2010 and purchasing cargo launchers to support two lunar missions a year starting in 2016. The less ambitious schedule would involve buying only 15 crew launchers for the ISS missions starting in 2012 and would delay the start of purchases for the lunar missions to beyond 2017.

a. The main propulsion system for the shuttle is composed of three "sticks": two four-segment solid rocket boosters attached to the central external tank (the third stick).

Alternative 2

Under this alternative, 29 crew launchers and eight cargo launchers would be purchased, CBO estimates (see Table E-2). The cost to develop and purchase those launchers would total about $26 billion over the 2006-2017 period, CBO estimates.

CBO assumed that the crew launcher would be a variant of the Atlas V Medium launcher, known as the Atlas V Medium Plus (A5M+). The A5M+ would feature a redesign of the first-stage booster core and second stage currently used on the Atlas family of medium launchers. The width of those stages would increase from just over 4 meters to slightly more than 5 meters, but the length of the booster core would decrease by about one-third. The first stage would be powered by two RD-180 engines, and the second stage would be powered by four RL-10 engines. Because the new launch system would be used as a crew launcher, state-of-the-art features would be added to aid in human flight, and more safety features would be added to conform with NASA's standards for manned launch.

According to CBO's estimates, the crew launcher would cost about $17 billion—roughly $5 billion in nonrecurring costs and about $12 billion in recurring costs (see Table E-2). The estimate of nonrecurring costs includes the following:

- about $2.2 billion for redesigning the current medium launcher to the A5M+ configuration, based on information from the Atlas V contractor;
- about $1.1 billion for conducting three test flights;
- about $0.3 billion for modifying launch pads;
- about $0.5 billion for equipping U.S. companies to manufacture all of the components of the Russian RD-180 engine; and
- about $1.2 billion for NASA overhead.

The estimate of recurring costs (about $12 billion) includes the cost of buying 29 A5M+ launchers, at an average price of about $400 million each, the same as the overall unit cost of the D4M+.

CBO assumed that the cargo launcher would be a variant of the Atlas V Medium launcher, known as the Atlas V Heavy Plus (A5H+). The A5H+ would use the same first-stage booster cores and second stage as the A5M+ crew launcher but would strap together three boosters in a manner similar to that used for the Delta IV Heavy launcher. Also, two RL-10 engines would be added to the second stage, bringing the total number of engines on the second stage to six. Those changes would allow the new launch system to be used as a cargo launcher with a payload lift of about 74 mt.

CBO estimates that the cargo launcher would cost about $9 billion—about $4 billion in nonrecurring costs and nearly $5 billion in recurring costs. The estimate of nonrecurring costs includes the following:

- about $0.2 billion to transition the A5M+ design to the A5H+ configuration, on the basis of information from the contractor regarding the needed redesign of the A5H+;
- about $1.6 billion for conducting three test flights;
- about $0.3 billion for modifying launch pads, on the basis of information provided by the contractor on the nature of the needed modifications;
- about $1 billion for deactivating NASA launch facilities; and
- about $0.9 billion for NASA overhead.

The estimate of recurring costs (about $5 billion) includes the cost of buying eight cargo launchers, at an average cost of about $600 million for each A5H+ (see Table E-1).

Alternative 3

CBO estimates that 29 crew launchers and eight cargo launchers would be purchased under this alternative. The cost to develop and purchase those launchers would total about $31 billion over the 2006-2017 period, CBO estimates.

CBO assumed that the crew launcher would use a variant of the space shuttle's solid rocket booster, known as the five-segment single stick. The five-segment single stick would be a two-stage launch vehicle. The first stage would be comparable to the SRBs used on the space shuttle, except it would add an extra segment of solid fuel to increase lift capability. A second stage would be added to

further increase lift capability. The second stage would be powered by a variant of the J-2S engine.

According to CBO's estimates, the crew launcher would cost about $18 billion—nearly $5 billion in nonrecurring costs and over $13 billion in recurring costs (see Table E-2). The estimate of nonrecurring costs includes the following:

- about $0.8 billion for redesigning the first-stage solid rocket boosters, based on NAFCOM estimates;
- about $2 billion for designing a second stage and the associated shroud, based on information from NAFCOM;
- about $1.3 billion for conducting three test flights; and
- about $0.7 billion for NASA overhead.

The estimate of recurring costs (more than $13 billion) includes the cost of buying 29 five-segment, single-stick launchers, at an average price of about $450 million each.

CBO assumed that the cargo launcher would be a variant of the space shuttle, known as the Side-Mount. The Side-Mount would consist of three main components—two SRBs, an external tank, and a payload carrier. This variant would be most similar to the space shuttle, minus the orbiter and with a payload carrier replacing it. The payload carrier would be powered by three space shuttle engines that burn liquid hydrogen and liquid oxygen to generate thrust. The two SRBs would be identical to those used on the space shuttle, and each would be powered by a solid rocket motor. The external tank would contain the propellants used by the three main engines on the payload carrier. The payload carrier would be positioned on the side of the external tank.

CBO estimates that the cargo launcher would cost over $12 billion—nearly $5 billion in nonrecurring costs and nearly $8 billion in recurring costs. The estimate of nonrecurring costs includes the following:

- about $0.1 billion for redesigning the solid rocket boosters and external tank to allow them to interface with the payload carrier, on the basis of NAFCOM estimates;
- about $0.9 million to design the payload carrier, on the basis of NAFCOM estimates;
- about $2.6 billion for conducting three test flights; and
- about $1.1 billion for NASA overhead.

The overall cost of each Side-Mount launcher would total about $950 million, CBO estimates—about the same as the cost for each space shuttle. The cost for buying eight of the launchers would total nearly $8 billion, CBO estimates.

Alternative 4

According to CBO's estimates, 29 crew launchers and four cargo launchers would be purchased under this alternative (see Table E-2). The cost to develop and purchase those launchers would total about $38 billion over the 2006-2017 period, CBO projects.

CBO assumed that the crew launcher would be the D4M+, the same launcher that would be used under Alternative 1. As mentioned earlier, CBO estimates that the nonrecurring costs would total about $3.5 billion and the recurring cost for buying 29 D4M+ launchers would total about $12 billion.

CBO assumed that the cargo launcher would use components of the Delta IV Heavy launcher but would represent a new design with much greater lift capability. The D4 super heavy would feature redesigned versions of the booster cores and second stage currently used on the Delta heavy launcher, allowing the super heavy to be used as a cargo carrier with a payload lift of nearly 150 metric tons—almost six times the lift capacity of the Delta IV Heavy launcher. The length of the boosters would increase by 50 percent and the width would increase by 60 percent, resulting in a mass increase of about 150 percent. Like the Delta IV Heavy launcher, each D4 super heavy would use three booster cores strapped together, but each booster would be powered by four RS-68 engines, an increase of three engines per core over the current Delta IV cores. The length of the second stage would increase by 100 percent, and the width would increase by 60 percent, resulting in a mass increase of about 220 percent. The second stage would be powered by one SSME that would be modified from its current configuration on the space shuttle.

The cargo launcher would cost about $23 billion—about $17 billion in nonrecurring costs and about $6 billion in recurring costs, CBO estimates (see Table E-2). The estimate of nonrecurring costs includes the following:

- about $3.6 billion for redesigning the Delta IV Heavy launcher to the D4 super-heavy configuration, on the basis of information from the Delta IV contractor;

- about $4.3 billion for conducting three test flights;

- about $5 billion for modifying launch pads, on the basis of information provided by the contractor on the nature of the needed modifications to Pad 39; and

- about $3.9 billion for overhead.

The estimate of recurring costs of about $6 billion includes the cost of buying four of the cargo launchers, an average cost of about $1.5 billion for each launcher (see Table E-1 for detailed information on the breakout of the recurring costs).

Alternative 5

CBO assumed that 29 crew launchers and four cargo launchers would be purchased under this alternative. The cost to develop and purchase the launchers, according to CBO's estimates, would total about $31 billion over the 2006-2017 period.

CBO further assumed that the crew launcher would be a variant of the Atlas V Medium launcher, known as the A5M+—the same crew launcher considered under Alternative 2. As stated earlier, CBO estimates that the nonrecurring costs would total over $5 billion and that the recurring costs for buying 29 of those launchers would total about $12 billion.

Under this scenario, CBO assumed that the cargo launcher would use components of the A5H+—the cargo launcher considered under Alternative 2—but, known as the A5 super heavy, it would have much greater lift capability. The A5 super heavy would use the same type of boosters as those featured on the A5H+ but would strap four of the boosters into a cluster. Each booster would be powered by two RD-180 engines. In the center of that cluster would be a fifth booster, slightly longer and wider than the other four boosters and powered by five RD-180 engines. Thus, the first stage would be powered by a total of 13 RD-180 engines. (The second stage of the A5 super heavy would correspond to that of the A5H+.) Those changes would allow the vehicle to be used as a cargo carrier with a payload lift of about 134 mt.

CBO estimates that the cargo launcher would cost nearly $14 billion—about $9 billion in nonrecurring costs and nearly $5 billion in recurring costs. The estimate of nonrecurring costs includes the following:

- about $1.4 billion to transition the A5H+ design to the A5 super-heavy configuration, based on information provided by the contractor about the design of the A5 super heavy;

- about $3.3 billion for conducting three test flights;

- about $1.2 billion for modifying the launch pads, based on information provided by the contractor and NASA analysts;

- about $1 billion for mothballing NASA launch facilities; and

- about $2.1 billion for NASA overhead.

The estimate of recurring costs of over $5 billion includes the cost of buying four cargo launches at an average of about $1.2 billion each—about twice the per-unit cost of an A5H+ launch.

Alternative 6

As with all the alternatives considered under the more ambitious schedule, CBO estimates that 29 crew launchers would be purchased under this scenario; four cargo launchers would be required (see Table E-2). The cost to develop and purchase those 33 launch vehicles would total about $32 billion over the 2006-2017 period, according to CBO's projections.

CBO assumed that the crew launcher would be the five-segment single stick, the same vehicle considered under Alternative 3. As discussed earlier, CBO estimates that the cost of this launcher would total about $18 billion—about $5 billion in nonrecurring costs and over $13 billion in recurring costs.

CBO assumed that the cargo launcher would use components of the space shuttle but have much greater lift capability. The Shuttle-derived super heavy would be a one-stage launch vehicle consisting of three main compo-

nents—two SRBs, an external tank, and a payload carrier. The two rocket boosters and the external tank would be strapped together to form the first stage. The rocket boosters would be identical to the booster used on the five-segment single-stick launcher. The external tank would be comparable to the tank used on the space shuttle and it would be powered by five SSMEs. Because those engines burn liquid hydrogen and liquid oxygen to generate thrust, placing five of them on the cargo launcher would provide lift capability of about 125 mt. The payload carrier would be positioned on top of the external tank.

The cargo launcher would cost about $14 billion, consisting of about $9 billion in nonrecurring costs and about $5 billion in recurring costs, according to CBO's estimates (see Table E-2). The projection of nonrecurring costs includes the following:

- about $1.1 billion for designing the external tank, on the basis of NAFCOM estimates;
- about $0.5 billion for designing the payload carrier, on the basis of NAFCOM estimates;
- about $3.5 billion for conducting three test flights;
- about $1.5 billion for modifying launch pads, on the basis of information provided by contractors about the nature of the needed modifications; and
- about $2 billion for NASA overhead.

The estimate of recurring costs of about $5 billion includes the cost of buying four cargo launchers, at an average of about $1.3 billion apiece (see Table E-1).

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